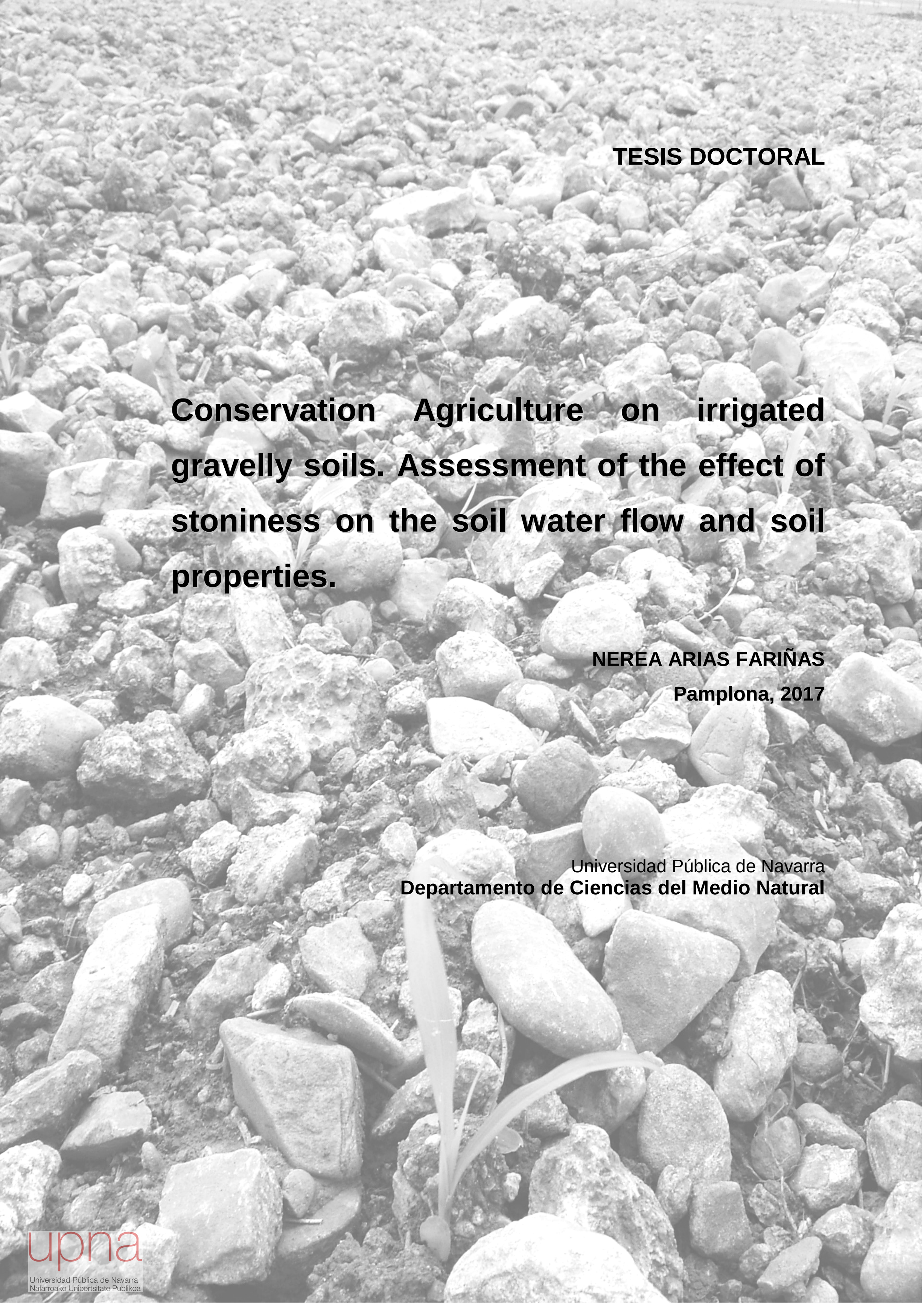

TESIS DOCTORAL

Conservation Agriculture on irrigated gravelly soils. Assessment of the effect of stoniness on the soil water flow and soil properties.

NEREA ARIAS FARIÑAS

Pamplona, 2017

Universidad Pública de Navarra
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Memoria presentada por

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Para optar al grado de Doctor por la Universidad Pública de Navarra

Conservation Agriculture on irrigated gravelly soils. Assessment of the effect of stoniness on soil water flow and soil properties.

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D. IÑIGO VIRTO QUECEDO, Profesor Contratado Doctor del Área de Edafología y Química Agrícola del Departamento de Ciencias del Medio Natural de la Universidad Pública de Navarra,

INFORMAN:

que la presente memoria de Tesis Doctoral titulada "***Conservation Agriculture on irrigated gravelly soils. Assessment of the effect of stoniness on soil water flow and soil properties***" elaborada por Dña. Nerea Arias Fariñas, ha sido realizada bajo nuestra dirección, y que cumple las condiciones exigidas por la legislación vigente **para optar al grado de Doctor.**

Y para que así conste, firma la presente en Pamplona a 26 de abril de 2017.

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La autora de esta tesis disfrutó desde septiembre de 2011 hasta septiembre de 2015, de una beca predoctoral del Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA), dentro del proyecto “Agricultura de conservación para cultivos de regadío y secano utilizando técnicas de producción integrada” (RTA2010-00006-C03-03).

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Muchas gracias a todos.
Eskerrik asko denoi.
Thank you very much everyone.

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TABLE OF CONTENTS

Resumen 3

Summary 7

Chapter I
Introducción 11
Marco de trabajo y estructura de la tesis 31
Objetivos de la tesis 39

Chapter II
Methodological considerations in the study of stoniness 45

Chapter III
Conservation agriculture in irrigated Mediterranean gravelly soils. Influence on crop production and soil properties 75

Chapter IV
Implications of rock fragments for soil organic C and soil quality evaluation: Assessing changes in a gravelly irrigated soil following no till adoption. 111

Chapter V
Effect of stoniness on the hydraulic properties of a soil from an evaporation experiment using the Wind and the Inverse Estimation methods.. 139

Chapter VI
Discusión General y Conclusiones 177

RESUMEN

Los suelos que contienen fragmentos de roca (partículas > 2 mm de diámetro) se denominan suelos pedregosos, y sólo en la región mediterránea cubren más del 60% de la superficie. Su uso para la producción de alimentos y fibras ha aumentado durante los últimos años debido a una mayor demanda de estos productos y a la expansión del regadío. Sin embargo, los estudios realizados no han prestado mucha atención a esta fracción gruesa, o a la influencia que ejerce sobre las diferentes propiedades del suelo. Por otra parte, se requiere que los agricultores practiquen una agricultura más sostenible y a este respecto la adopción de los principios de la Agricultura de Conservación podría ser una estrategia válida. Sin embargo, el efecto de su adopción en suelos pedregosos bajo condiciones de regadío no es del todo conocido. Por lo tanto, el objetivo de este trabajo fue ampliar el conocimiento sobre estos aspectos.

Esta tesis se divide en diferentes capítulos enfocados a la caracterización de la pedregosidad y al efecto de la introducción de técnicas de Agricultura de Conservación en las propiedades de suelos pedregosos en condiciones de regadío. Además, se aborda el efecto que la presencia de fragmentos de roca ejerce sobre las propiedades tanto químicas como hidráulicas del suelo.

En primer lugar, en el capítulo II, se ofrece una visión general de las características más importantes para la cuantificación de los fragmentos de roca, así como para interpretar su relevancia en el funcionamiento del suelo. Además, se realizó una revisión de diferentes cuestiones metodológicas relacionadas con la determinación de la pedregosidad del suelo considerando tres aspectos: la estrategia de muestreo, la utilidad de los enfoques geoestadísticos y la estimación por métodos indirectos. Para ello se realizó un experimento de campo donde se aplicaron diferentes métodos de muestreo. Los resultados mostraron que una cuantificación correcta de los fragmentos de roca se consiguió solamente al utilizar un volumen de suelo lo suficientemente representativo. Se demostró que el análisis geoestadístico es útil para evaluar la variabilidad en el diseño del muestreo de campo y para detectar patrones espaciales que pudieran inducir sesgos en el análisis del suelo. Además, se evaluó la validez de estimar la pedregosidad mediante el análisis de imágenes a partir de una colección de fotografías del suelo. Esta técnica necesita un mayor desarrollo, pero en cualquier caso se obtuvieron mejores resultados para suelos con un contenido de fragmentos de roca inferior al 20%. Hay que destacar que para la adquisición exitosa de fotografías hay que evitar la presencia de sombras, plásticos, residuos

de cultivos, suelos recientemente arados o suelos con una matriz de un color similar a sus fragmentos de roca.

El efecto de la adopción de técnicas de Agricultura de Conservación se abordó en el capítulo III. Los efectos de la introducción de esta práctica fueron evaluados para suelos con fragmentos de roca en regadío. La producción de cultivos, la fertilidad del suelo, la materia orgánica y las características de retención y conservación del agua del suelo fueron monitorizados en una parcela experimental pedregosa localizada en el NE de España bajo dos tratamientos: laboreo convencional (CT) y no laboreo (NT). A pesar de la menor emergencia de plantas bajo NT, no se encontraron diferencias en la producción de los cultivos. Los resultados también mostraron que la mayor protección o menor perturbación de los residuos de los cultivos bajo NT aumentaron la fertilidad del suelo, la materia orgánica y la capacidad de retención de agua de este tipo de suelos en un período muy corto de tiempo. Además, la presencia de restos de cultivo que permanecen en el suelo bajo esta práctica redujo la evaporación. Por lo tanto, el NT se posiciona como una estrategia válida para aumentar la fertilidad del suelo y la materia orgánica, al mismo tiempo que optimiza la eficiencia del uso del agua en suelos pedregosos en regadío.

La Agricultura de Conservación podría ser adoptada en suelos pedregosos para aumentar su protección contra la degradación, así como mejorar su calidad. Sin embargo, la evaluación de los cambios debidos al manejo en estos suelos puede ser problemática. Es por ello que el efecto de esta práctica sobre la materia orgánica del suelo y su calidad se evaluó más a fondo en el capítulo IV. Para ello, se monitorizó el N y el C orgánico total, particulado y mineralizable, así como su estratificación en profundidad, pero también se evaluaron las implicaciones que tiene la presencia de fragmentos de roca para la calidad del suelo y para la conversión de los contenidos de C y N a unidades de superficie. A pesar de las ganancias de hasta 10 Mg C ha^{-1} que se observaron en la capa labrada (0-30 cm) para ambos tratamientos, la presencia de materia orgánica en la capa superior del suelo (0-5 cm) bajo NT fue mayor y, por tanto, estaba más estratificada. Sin embargo, una distribución de fragmentos de roca heterogénea a lo largo del perfil del suelo afectó a este resultado al referirlo a todo el volumen, no sólo a la tierra fina. Por otro lado, la materia orgánica lábil destacó como un indicador de calidad del suelo sensible a los cambios de manejo, incluso tras la corrección del contenido de fragmentos de roca. Este trabajo también mostró la necesidad de considerar de manera cuidadosa la metodología seleccionada para calcular el stock de C del suelo porque una elección inapropiada puede sobrestimar su contenido.

Además de lo anterior, se desconoce el efecto que los fragmentos de roca ejercen sobre las propiedades hidráulicas del suelo, ya que son complicadas de medir *in situ* en este tipo de suelos. Es por ello que generalmente se calculan por otros medios. En el capítulo V se evaluó la idoneidad de la estimación de las propiedades hidráulicas de un suelo pedregoso a partir de las propiedades de su tierra fina corrigiendo éstas por el volumen ocupado por los fragmentos de roca. Estas propiedades se estimaron utilizando los datos de un experimento de evaporación en el que el contenido de agua del suelo y la presión de succión se midieron a lo largo del tiempo. También se evaluó la validez de las diferentes metodologías utilizadas para esta estimación (el Método del Perfil Instantáneo, el método de Wind y la Estimación Inversa). Los resultados mostraron que estas metodologías fueron válidas para estimar el contenido de agua del suelo y la conductividad hidráulica, a excepción de algunas incertidumbres derivadas del limitado rango de succión en el que se realizó el experimento. La aplicación de la corrección explicada anteriormente resultó en un enfoque simplificado que no tuvo en cuenta el efecto que los poros creados por la presencia de fragmentos de roca en el suelo pueden ejercer sobre los procesos de flujo de agua.

En resumen, el trabajo realizado bajo la presente tesis supone un avance en la comprensión de los suelos pedregosos y su interacción con las prácticas de Agricultura de Conservación bajo condiciones de regadío. Específicamente, se ha incrementado el conocimiento sobre los aspectos que hay que considerar cuidadosamente al evaluar los cambios de manejo en estos suelos y también las implicaciones que conlleva una correcta cuantificación de los fragmentos de roca, así como su efecto sobre la fertilidad del suelo, la materia orgánica, la calidad del suelo y las propiedades hidráulicas.

SUMMARY

Soils tan contain rock fragments (particles > 2 mm of diameter) are denoted as stony soils, and only in the Mediterranean region they account for more than 60% of the land. Their use for food and fibre production has increased during the last years due to a higher demand of these products and to the expansion of irrigation. However, studies have not paid much attention to this coarse fraction, or to the influence it exerts on different soil properties. On the other hand, farmers are requested to practice a more sustainable agriculture. The strategy of adopting Conservation Agriculture principles may fulfil this demand. Still, the effect of its adoption on these stony soils under irrigation is not well understood. Therefore, the objective of this work was to gain knowledge on these aspects.

This thesis was divided into different chapters focused on the characterization of stoniness and the effect of introducing Conservation Agriculture techniques on soil properties in these types of soils under irrigation systems. Besides, the effect that rock fragments presence exerts on chemical and hydraulic properties was addressed.

Firstly, chapter II provides an overview of the most important features for rock fragment quantification and also for interpreting its relevance on soil functioning. In addition, a review of different methodological issues related to soil stoniness determination was provided considering three aspects: the sampling strategy, the usefulness of geostatistical approaches and also the estimation by indirect methods. A field experiment was conducted where different sampling methods were tested. Results showed that a correct quantification of rock fragments was successfully achieved only when a volume representative enough was used. Geostatistical analysis was proven useful for assessing the adequacy of the field sampling scheme and to detect spatial patterns that could induce bias on soil analysis. Besides, the validity of estimating stoniness by image analysis was tested on a collection of soil photographs. This technique needs further development but better results were achieved for soils with a rock fragment content lower than 20%. The key for successful photograph acquisition relayed on avoiding shadows, plastics, crop residues, soils recently ploughed, or soils with a matrix of a similar colour to its rock fragments.

The effect of adopting Conservation Agriculture techniques was addressed in chapter III. The effect of introducing this practice was evaluated for soils with rock fragments under irrigation conditions. Crop

production, soil fertility, organic matter, and soil water retention and conservation characteristics were monitored in a gravelly experimental field located in the NE of Spain under two treatments: conventional tillage (CT) and no-tillage (NT). Despite lower plant emergences under no-tillage, no differences were found for crop production. Results also showed that the protection or less disturbance of crop residues under NT increased soil fertility, organic matter and the upper water holding capacity of this type of soils in a very short period of time. Furthermore, the presence of crop residues left on the soil under this practice reduced evaporation. Thus, NT seemed a valid strategy for increasing soil fertility and organic matter while optimizing water-use efficiency in irrigated gravelly soils.

Conservation Agriculture may be adopted in stony soils for increasing their protection against degradation and enhancing their quality. This is why the effect of this practice on soil organic matter and its quality was more thoroughly assessed in chapter IV. However, the assessment of management changes on these soils can be troublesome. Therefore, total, particulate and mineralizable organic C and N, and their stratification with depth were monitored, but also the implications of rock fragments presence for soil quality and for converting C and N contents to area units was assessed. Despite gains of C up to 10 Mg C ha^{-1} were observed in the tilled layer (0-30 cm) for both treatments, the presence of organic matter at the topsoil layer (0-5 cm) under NT was higher and, hence, more stratified. However, a heterogeneous rock fragment distribution through the soil profile had an effect on this result when referred to the whole soil volume, not only the fine earth. In addition, the labile organic fraction stood out as a sensitive soil quality indicator to management changes, even after rock fragments content correction. This work also showed that careful consideration is needed in the selection of a methodology for soil C stock calculations in stony soils, because an inappropriate choice may overestimate its content.

In addition, there is a lack of knowledge on the effect rock fragments exert on soil hydraulic properties because they are complicated to measure *in situ* in this type of soils. Therefore, they are usually estimated by other means. Chapter V assessed the adequacy of estimating stony soil hydraulic properties from the fine earth ones by correcting the latter by the volume the rock fragments occupy. These properties were estimated using data from an evaporation experiment where the soil water content and pressure heads were measured over time. The validity of different methodologies used for the estimation (the Instantaneous Profile Method, the Wind method, and the Inverse Estimation) was also evaluated. Results showed that these different methodologies were valid to estimate the soil water content and the hydraulic conductivity, except for some uncertainties derived from the limited range of suction in which the experiment was conducted. The application of the correction explained before resulted in a simplified approach that did not take into account the effect that pores created by the presence of rock fragments in the soil likely exert on water flow processes.

In summary, the work conducted in this thesis constitutes an advance on understanding stony soils and their interaction with Conservation Agriculture practices under irrigation. Specifically, more knowledge has been gained on the aspects that have to be carefully considered in stony soils when assessing management changes and also the implications for a correct rock fragment quantification and their effect on soil fertility, organic matter, soil quality and hydraulic properties.

Chapter I

Introducción

Marco de trabajo

Objetivos de la tesis

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CHAPTER I

Introducción y objetivos de la tesis

Contenidos

INTRODUCCIÓN

1. La Pedregosidad **14**

Características generales y distribución 14

Influencia en las propiedades del suelo 16

2. Agricultura en regadío **20**

Distribución mundial 20

Influencia del riego 22

3. Agricultura de Conservación (AC) **25**

Características generales 25

Distribución mundial de la AC 27

Influencia en las propiedades del suelo y en los cultivos 27

MARCO DE TRABAJO Y ESTRUCTURA DE LA TESIS **31**

OBJETIVOS DE LA TESIS **39**

REFERENCIAS **40**

INTRODUCCION

1. La Pedregosidad

Características generales y distribución mundial. La pedregosidad es una característica del suelo que se puede definir como el volumen relativo de los fragmentos de roca presentes en el mismo (FAO, 2006). Este volumen es variable, y puede presentar valores muy bajos, incluso despreciables, o ser importante, llegando a provocar problemas agronómicos.

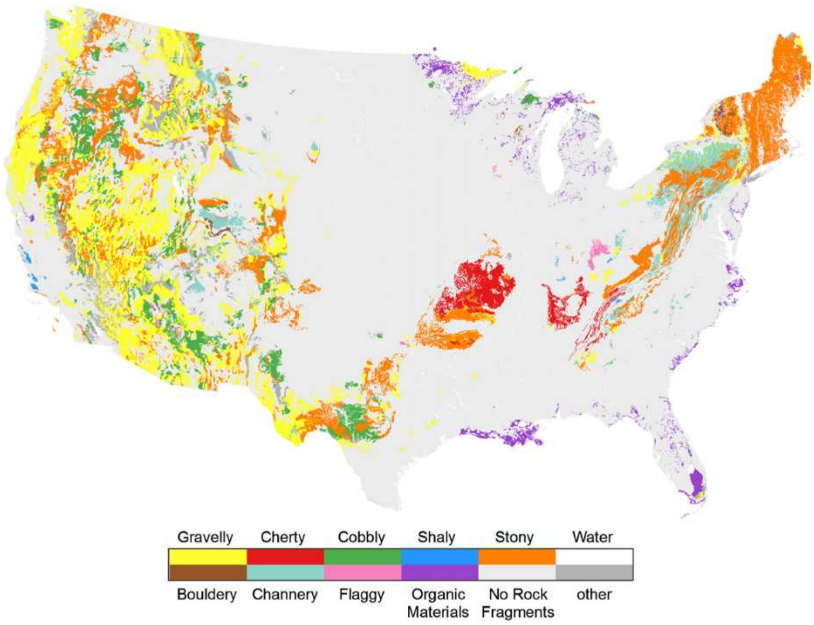

Figura 1. Mapa de suelos pedregosos en Estados Unidos (Throop et al., 2012).

La mayor parte de estudios del suelo se han centrado en la tierra fina (partículas < 2 mm), sin prestar mucha atención a esta fracción más gruesa que, sin embargo, está ganando importancia en los últimos años debido a su extensión y al uso cada vez mayor de suelos pedregosos para la producción de fibras y alimentos (Poesen y Lavee, 1994; Novák y Surda, 2010; Beckers et al., 2016). Este tipo de suelos se encuentran distribuidos por todo el mundo bajo diferentes condiciones climáticas y tipos de usos (Smets et al., 2011) especialmente en aquellos lugares formados a partir de la meteorización mecánica de la roca madre, o donde la tierra fina se ha perdido por erosión (Stendahl et al., 2009). Por ejemplo, en África, los suelos con gravas están distribuidos por el Sahara, el Sahel, así como en la parte oeste del continente (Jones et al., 2013).

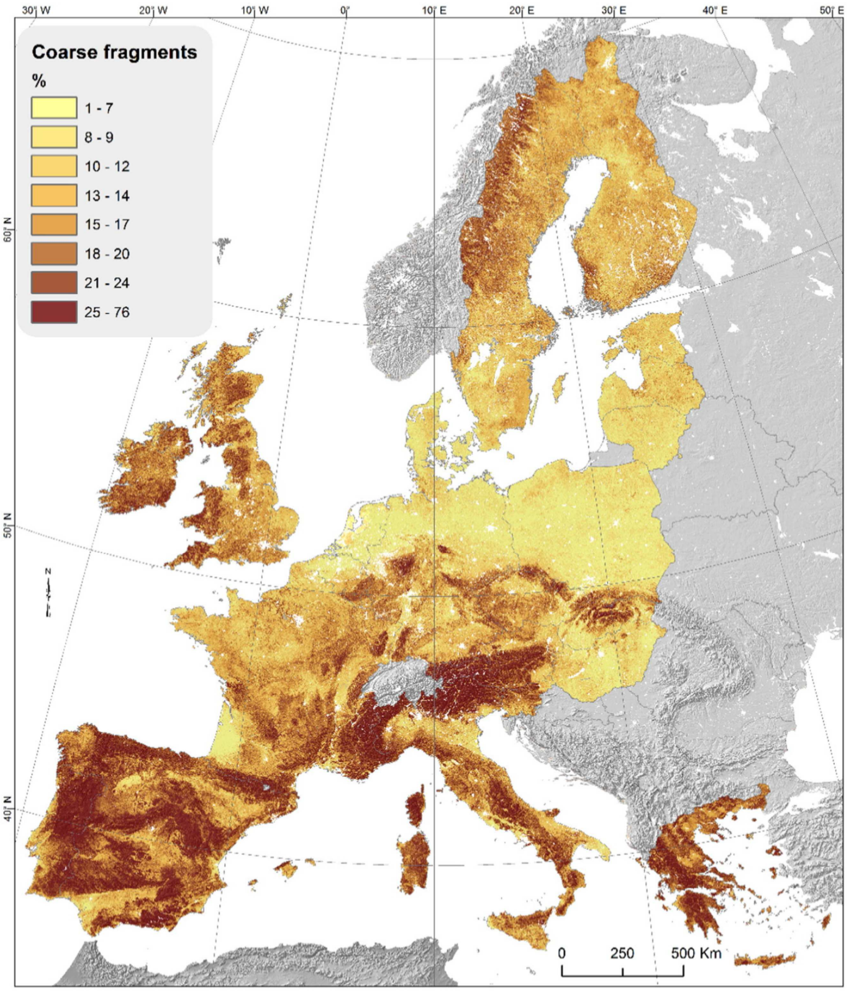

Figura 2. Mapa de la distribución de los fragmentos de roca (%) representados a escala europea a una profundidad de 0-20 cm modelado por el método “Multivariate Additive Regression Splines” (Ballabio et al., 2016).

Suelos con una pedregosidad comprendida entre el 15 y el 80% pueden encontrarse en Centroamérica, además de otras áreas de

Chile, Perú, Venezuela, Brasil (Gardi et al., 2014) o Estados Unidos tal y como se observa en la Figura 1 (Throop et al., 2012). Solamente en el área Mediterránea, el 60% del territorio está cubierto por suelos que contienen cantidades significativas de fragmentos de roca (> 10% de la masa total del suelo) (Poesen y Lavee, 1994). Esto es especialmente relevante en países como España, tal y como se puede observar en el mapa mostrado en la Figura 2, desarrollado por Ballabio et al. (2016). Por lo tanto, parece de vital importancia incrementar el conocimiento de las características e implicaciones de la presencia fragmentos de roca en el suelo.

Influencia en las propiedades del suelo. La presencia de fragmentos de roca en el suelo puede tener diferentes consecuencias ya que puede modificar propiedades físicas tales como la temperatura, la disponibilidad de agua en el suelo, la infiltración o la susceptibilidad a la escorrentía y la dinámica de flujo de agua; las propiedades químicas como los contenidos de carbono o nitrógeno; o las características agronómicas como el rendimiento (van Wesemael et al., 1996; Cousin et al., 2003; Andrades et al., 2007; Stendahl et al., 2009).

La **infiltración, junto con la susceptibilidad a la escorrentía** ha sido estudiada en mayor profundidad. Es posible encontrar opiniones encontradas en la literatura con respecto al efecto que ejercen los fragmentos de roca en ellas (Poesen et al., 1990; Brakensiek y Rawls, 1994; Yang et al., 2013). Sin embargo, existe consenso en que uno de los factores condicionantes principales es la posición en la que dichos fragmentos se encuentran en la superficie. En el caso de encontrarse libres, contribuyen a evitar el sellado superficial y por tanto la infiltración se incrementa (Cousin et al., 2003). Una explicación simplificada radica en que cuando se produce un episodio de lluvia, los fragmentos de roca protegen la capa superficial del suelo de los impactos de las gotas de agua reduciendo la degradación física (Smets et al., 2011). Por el contrario, cuando están incrustados en la superficie, pueden contribuir a la creación de una costra superficial que incrementa la escorrentía al limitar la infiltración (Poesen y Lavee, 1994; Cousin et al., 2003).

Además de los efectos que genera la presencia de fragmentos de roca en la capa más superficial, el **movimiento de agua en el suelo** se ve afectado por la presencia de estos fragmentos cuando están situados dentro del perfil. Su presencia disminuye la conductividad hidráulica al reducirse el área efectiva por la que el agua puede circular e incrementar la tortuosidad del flujo (Ravina y Magier, 1984). Esta hipótesis ha llevado a que se modelice la conductividad hidráulica de los suelos pedregosos a partir de la obtenida para la tierra fina. Sin embargo, la interacción entre la tierra fina y los fragmentos de roca no es tan simple, ya que se pueden producir cambios en la estructura y distribución del espacio poroso. Esto es debido a que la presencia de fragmentos rocosos que favorece la creación de nuevos poros a través de los cuales se facilita el flujo de agua (Sauer y Logsdon, 2002; Verbist et al., 2008; Baetens et al., 2009). Por lo tanto, comprender la relación entre las propiedades hidráulicas del suelo y los fragmentos de roca resulta difícil (Beckers et al., 2016). En cualquier caso, algunos autores han establecido un umbral entre la acción positiva o negativa que ejercen los elementos gruesos en las propiedades hidráulicas del suelo. A partir de dicho umbral, la conductividad hidráulica disminuye independientemente de la posible presencia de macro poros generados por los fragmentos de roca presentes en el suelo. Esto es consecuencia del gran tamaño de los poros creados, que disminuyen su capacidad para conducir el agua rápidamente conforme el suelo se va secando. Su valor discrepa de unos autores a otros tomando valores desde el 15% al 40% (Verbist et al., 2008; Yang et al., 2013).

En el caso de **la disponibilidad de agua del suelo**, el efecto que tiene la presencia de fragmentos de roca es complejo, ya que también depende de muchos factores. Generalmente, a mayor porcentaje de fragmentos de roca, menor es la disponibilidad de agua de ese suelo (Cousin et al., 2003; Baetens et al., 2009). Sin embargo, hay que tener en cuenta que, dependiendo de su origen, estos fragmentos pueden ser capaces de retener agua, como es el caso de la creta, o de no retener nada como en el caso de rocas ígneas de muy baja porosidad (Brakensiek y Rawls, 1994; Ingelmo et al., 1994; Poesen y Lavee, 1994; Cousin et al., 2003; Novák y Surda, 2010).

Por lo tanto, aunque los fragmentos de roca reducen la capacidad de retención de agua de manera global (Novák y Knava, 2012), también pueden contribuir en el agua disponible para las plantas. El tamaño y la porosidad de los fragmentos puede ser un factor influyente también ya que los fragmentos más pequeños tienden a estar más meteorizados, y por consiguiente presentan una mayor capacidad de retener agua. (Poesen y Lavee, 1994; Cousin et al., 2003).

Por lo tanto, debido a la complejidad existente en la interacción tierra fina – fragmentos de roca, la estimación de las propiedades hidráulicas de los suelos pedregosos a partir de las propiedades de la tierra fina utilizando meramente la corrección por el volumen que ocupan los elementos gruesos en el volumen total del suelo puede resultar demasiado simplificada y necesita más investigación.

Cuando se repasa la literatura existente, la mayoría de estudios tanto agronómicos como de ciencia del suelo refieren los resultados a la fracción fina, ya que es la fracción con la que por consenso se determinan las propiedades del suelo y se realizan los análisis de laboratorio más característicos. Sin embargo, es necesario que en todos los **estudios tanto de la materia orgánica como de nitrógeno o cualquier otra propiedad del suelo**, se tenga en cuenta la pedregosidad existente (Torri et al., 1994; Stendahl et al., 2009). Cuando no se hace o se omite, las propiedades del suelo no se evalúan correctamente dando lugar a sobrestimaciones (Stendahl et al., 2009; Cousin et al., 2013). Además, existen otras fuentes de error relevantes en el estudio de los contenidos de carbono o nitrógeno en suelos pedregosos. La cuantificación de los fragmentos de roca puede generar un problema ya que las técnicas habituales empleadas para el muestro del suelo pueden no ser las más adecuadas para aquellos que presenten fragmentos de roca. Por otro lado, la conversión de stocks a unidades de área o volumen no es fácil debido a la dificultad del muestreo de la densidad aparente en estos suelos (Eriksson y Holmgren, 1996; Auerswald and Schimmack, 2000), pero también al proceso de cálculo de conversión en sí mismo en el que se pueden introducir interpretaciones erróneas al seleccionar la fracción sobre la que se aplican los cálculos. Por último, aquellos estudios enfocados a evaluar indicadores de calidad en suelos con elementos gruesos podrían verse afectados por la distribución de dichos elementos a lo largo del perfil del suelo o por la falta de idoneidad de los indicadores en sí mismos (Stendahl et al., 2009; Rytter, 2012; Trhoop et al., 2012). Además, a aquellos estudios utilizados para extrapolar las propiedades del suelo a nivel regional, nacional o a cualquier otra escala, hay que sumarle la variabilidad espacial que presentan los fragmentos de roca (Rytter, 2012). Esto es especialmente relevante en estudios sobre la resiliencia de un suelo frente a impactos ambientales, en la evaluación de cambios en el manejo o de su capacidad para almacenar carbono contribuyendo a frenar el cambio climático.

La relación entre fragmentos de roca y la **productividad de un suelo** es variable y depende de múltiples factores como el contenido total de fragmentos de roca, el tipo de vegetación o la climatología. Relaciones negativas con la productividad se atribuyen al menor volumen disponible para nutrientes ya que resulta evidente que cuanto mayor sea la fracción gruesa, menor es el contenido de tierra fina (Poesen y Lavee, 1994; Rytter, 2012). Sin embargo, la cantidad de inputs que recibe un suelo pedregoso es el mismo, por lo que en la mayoría de los casos se concentran en la fracción fina (Poesen y Lavee, 1994; Stendahl et al., 2009). Además, dependiendo del tipo de textura, la presencia de fragmentos de roca puede ser beneficiosa para la producción vegetal, como en el caso de texturas arcillosas. En climas áridos o semiáridos la presencia de fragmentos de roca, hasta un nivel moderado, parece más beneficiosa para la producción vegetal que en climas más húmedos debido a su capacidad para incrementar la disponibilidad de agua y el régimen de temperaturas. Sin embargo, un contenido mayor del 10 - 30% del volumen total del suelo podría llegar a ser desfavorable para el desarrollo de las raíces incrementando además la temperatura del suelo hasta niveles perjudiciales para el desarrollo vegetal (Poesen y Lavee, 1994). En cualquier caso, para que la vegetación se pueda aprovechar de los efectos beneficiosos de la presencia de los fragmentos gruesos del suelo, es necesario que desarrollen un sistema radicular capaz de penetrar este tipo de suelos (Ingelmo et al., 1994).

Por todo ello es importante realizar una adecuada caracterización de los suelos pedregosos de manera que puedan ser manejados y aprovechados de la mejor manera posible en función de su potencial y de sus limitaciones (Andrades et al., 2007).

2. Agricultura en regadío

La agricultura de secano es la más extendida a nivel mundial. Dentro de los factores que intervienen en la producción, el agua se sitúa como un elemento limitante en el desarrollo de los cultivos. Cuando la evapotranspiración de estos es mayor que las precipitaciones que reciben, se suelen producir descensos de producción. Esto es especialmente relevante en las zonas áridas y semiáridas. Es por ello que en estas zonas el potencial productivo de ciertos cultivos no es tan alto como en zonas con mayores precipitaciones medias. Además, estas características hacen que la incorporación de diferentes cultivos a la rotación no se pueda contemplar como alternativa. Por lo tanto, el regadío es útil en este tipo de regiones, ya que puede mejorar la calidad de los cultivos (principalmente en hortícolas), incrementar los rendimientos, aumentar la oportunidad de introducir cultivos diferentes en las rotaciones, hacer doble cultivo (dos cultivos por año) o aplicar fertilizantes por riego. Asimismo, el regadío hace posible la agricultura en zonas que previamente no eran adecuadas o estaban limitadas, como puede ser el caso de suelos pedregosos.

Distribución mundial. Según los datos de la FAO (2011), el número de hectáreas cultivadas bajo regadío se ha doblado durante los últimos 50 años y actualmente suponen el 20% de la tierra cultivable. Más allá, se espera que la superficie bajo regadío se incremente hasta más de 320 millones de ha en los próximos años, lo que conllevaría un incremento del 6% respecto a 2009.

En España, el regadío ha supuesto históricamente un incremento del potencial productivo con respecto al secano en su implantación en regiones con escasa pluviometría como la Mediterránea. La evolución de la agricultura en regadío sigue una tendencia al alza situándose alrededor de los 3,7 millones de hectáreas durante el año 2015, lo que supone alrededor del 14% de la superficie agraria útil. Los cereales son los cultivos que más superficie ocupan en el regadío, aunque los cultivos en los que más uso de agua se realiza son los cítricos y las hortalizas (MAPAMA, 2015). Sin embargo, a pesar de la escasez del recurso agua, el volumen de agua de riego utilizado es elevado, lo que está impulsando sistemas productivos más eficientes en el uso de los recursos (MAPAMA, 2017).

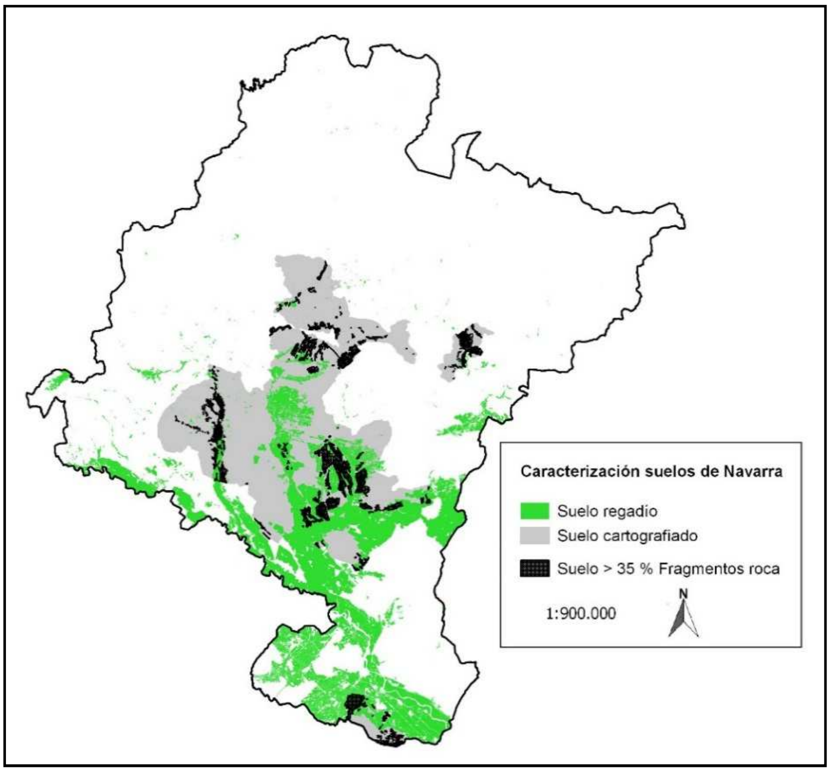

Figura 3. Mapa de suelos con más de un 35% de fragmentos de roca dentro de la superficie cartografiada y superficie de suelo en regadío en Navarra.

A nivel más local, en Navarra, se decidió promover la transformación de tierras a regadío con el objetivo de impulsar la productividad de las zonas agrarias con menos pluviometría ya que, en esas zonas, el cultivo de cereal no alcanzaba la rentabilidad suficiente para la supervivencia de las explotaciones. Este es el contexto en el que se desarrolló el proyecto del Embalse de Itoiz - Canal de Navarra – Zonas Regables dentro del Plan Hidrológico Nacional y del Plan Nacional de Regadíos, cuyo objetivo es convertir alrededor del 60% de la superficie agraria de secano en regadío, mejorar regadíos tradicionales para hacerlos más eficientes, e impulsar el desarrollo rural de dichas zonas. La primera fase supuso una transformación de más de 22.000 ha. Actualmente se está realizando una ampliación de esa primera fase con alrededor de 10.000 ha más, y el resto se pondrá en marcha en el futuro con la segunda fase del proyecto (Gobierno de Navarra, 1995; Gobierno de Navarra, 2012).

Por lo tanto, la introducción del regadío ha permitido que parcelas con ciertas limitaciones para la producción en secano debido a sus características intrínsecas, como es el caso de los suelos pedregosos, sean capaces de obtener rendimientos altos al transformarse el régimen de humedad. En el mapa mostrado en la Figura 3 se pueden observar los suelos pedregosos en Navarra que pertenecen a la familia esquelética, es decir, presentan más de un 35% de piedras en la superficie controlada. Además, se muestran aquellos suelos que actualmente se encuentran bajo un sistema de regadío (Gobierno de Navarra, 1995). A pesar de que no hay información cartográfica de suelos de gran parte de la superficie de Navarra (la parte gris es la parte cartografiada), se puede observar que los suelos con abundante pedregosidad están distribuidos por diferentes zonas, algunas de ellas bajo regadío. Además, es posible suponer que la superficie real será mayor que la indicada en la Figura 3. Así mismo hay que tener en cuenta que esta figura sólo representa una parte de los suelos de la región donde la pedregosidad es > 35%, por lo tanto, la presencia de suelos en regadío con una cantidad importante de fragmentos de roca (aunque sea inferior a dicho 35%) es presumible que sea bastante mayor.

Influencia del riego. Como se ha descrito anteriormente, la principal ventaja que ofrece el regadío es la posibilidad de incrementar el desarrollo de los cultivos, y por lo tanto la biomasa vegetal (Denef et al., 2008; Apesteguía et al., 2015). Esto tiene asociado un incremento potencial de los inputs que recibe el suelo en forma de residuos de cultivo, lo cual también depende del manejo. De la misma manera se produce el mismo efecto de incremento de inputs cuando dentro de las rotaciones se introducen cultivos con mayor capacidad para producir biomasa. Por lo tanto, en los suelos recientemente convertidos a regadío las producciones de los cultivos habituales de secano son mayores, o se introducen cultivos capaces de generar mayor masa vegetal, lo que conlleva mayor volumen de residuos (Sainju et al., 2012; Cotton et al., 2013). Estos residuos vegetales tanto aéreos como subterráneos son importantes para el incremento del carbono orgánico del suelo (SOC). El incremento de este SOC, a través del retorno de carbono en forma de residuos, es función de la cantidad y calidad de los residuos, del manejo y de las propiedades del suelo. Por consiguiente, el incremento en la producción que conlleva mayores inputs de carbono al suelo, en conjunto con el cambio en el régimen de humedad, puede provocar que el mayor contenido de carbono entrante tienda a acumulase. Esto puede continuar hasta que se alcance una nueva situación de equilibrio con el C saliente debido a la mineralización. El nuevo estado alcanzado será mantenido hasta que cambios de manejo, de las condiciones climáticas o de algún otro factor causen un nuevo cambio (Follet, 2001) tal y como se puede observar en la Figura 4.

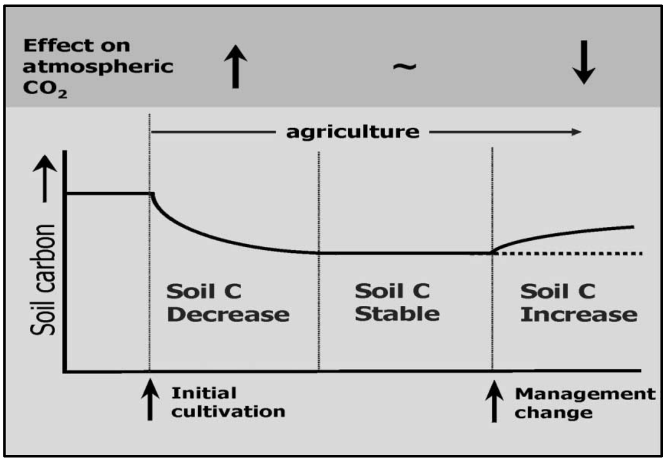

Figura 4. Cambios en el secuestro de carbono del suelo a largo plazo y su emisión como dióxido de carbono en función de las prácticas agrícolas (Follet, 2001).

A pesar de que el cambio a regadío podría suponer una superación de las restricciones para la acumulación de C típicas de los agroecosistemas Mediterráneos debido a la falta de precipitación y bajos inputs (Álvaro-Fuentes y Paustian, 2011), este cambio de manejo podría tener un efecto limitado debido a la estimulación de la actividad microbiana y a la descomposición de la materia orgánica (Gillabel et al., 2007). Cotton et al. (2013) observaron un incremento de la actividad microbiana en un periodo corto de tiempo (dos campañas) debido a la transformación de una parcela de secano a regadío en la que se introdujo un cultivo con gran capacidad para producir residuos como el sorgo. Por otro lado, De Bona et al. (2008) advirtieron una mayor tasa de mineralización del carbono en regadío en comparación con el secano, que compensaba las mayores entradas de carbono en el sistema derivadas de una mayor producción de residuos. Tanto Gillabel et al. (2007) como Denef et al. (2008) observaron un incremento del almacenamiento de carbono en los 20 primeros centímetros del suelo bajo regadío en comparación con el secano, aunque limitado debido al aumento de la actividad microbiana. A esto hay que sumarle que en los sistemas agrícolas bajo regadío generalmente se realiza un laboreo más intenso, los residuos de los cultivos pueden ser aprovechados en vez de incorporase al suelo e incluso se podría llegar a perder SOC debido a la erosión potencial de este tipo de suelos (Follet, 2001).

Por otro lado, la agricultura de regadío también puede producir una serie de efectos negativos siempre que no se realice un buen manejo de los recursos, tanto del agua como del suelo. En el caso de la aspersión, puede influir negativamente en la estructura del suelo, así como en la formación de costras debido al efecto que producen los impactos de las gotas de agua sobre el terreno (Gillabel et al., 2007). Asimismo, cuando se riega con aguas de baja calidad que contengan sales disueltas, o en suelos con drenajes deficientes, se puede producir un incremento de la salinidad o incluso de la sodicidad, degradando seriamente la calidad de dichos suelos. Además, el regadío generalmente va asociado a una intensificación que implica un incremento en el uso de inputs como fertilizantes o fitosanitarios que pueden conllevar riesgos para el medio ambiente

(FAO, 2011) dependiendo en última instancia del manejo que se haga de los mismos.

Por todo ello, es necesario que en esta agricultura más intensificada se pongan en práctica las mejores prácticas o manejos adaptados a los ecosistemas locales que ya se están utilizando en secano, como es el caso de la agricultura de conservación (FAO, 2011). Sin embargo, hay que señalar que, a pesar de la importancia de la gestión de los recursos en estos sistemas, no existen muchas investigaciones acerca de los efectos que diferentes manejos pueden acarrear sobre los cultivos, los suelos o el medio en condiciones de regadío en condiciones semiáridas mediterráneas. Más allá, sería necesario incrementar el número de estudios existentes en los agrosistemas en regadío para evaluar cuál es el potencial real de secuestro de carbono, y las consecuencias de diferentes estrategias de manejo en la calidad del suelo bajo estos diferentes manejos.

3. Agricultura de Conservación

Características generales. En muchas regiones del mundo la preocupación por la protección del medio ambiente y de los recursos naturales, como por ejemplo el suelo, es cada vez mayor. En el contexto europeo, esto ha llevado a que la sostenibilidad medioambiental cobre un papel relevante en las políticas agrarias. Como consecuencia, la investigación y la puesta en práctica de técnicas o manejos agrícolas considerados sostenibles por su optimización y conservación de los recursos naturales es necesaria.

La Agricultura de Conservación (AC) es una estrategia adecuada a este respecto ya que su objetivo, tal y como lo define la FAO (2003), es manejar los agrosistemas de manera que se mejore y sostenga la productividad, se incrementen los beneficios y la seguridad alimentaria al mismo tiempo que se preserva el medio ambiente. Para ello se basa en tres principios:

1. Un continuo no laboreo (sembrar directamente sin realizar preparaciones previas del terreno) o una mínima perturbación mecánica del suelo evitando siempre el volteo.

2. Cubierta orgánica permanente del suelo con los residuos de los cultivos o mediante cubiertas vegetales. Cuando se realiza un mínimo laboreo al menos el 30% de los restos del cultivo anterior deben permanecer sobre la superficie del suelo.

3. Diversificar las especies de cultivos en secuencias o asociaciones a través de rotaciones o en el caso de cultivos permanentes, mediante asociaciones de plantas.

Indudablemente una de las ventajas más interesantes que aporta la adopción de esta práctica, tanto a nivel agrícola como social, es la estabilización de la estructura del suelo, así como la protección del mismo frente a los impactos de las gotas de lluvia, disminuyendo de esta manera la erosión y por lo tanto las pérdidas por escorrentía que provocan problemas de sedimentación corriente abajo (Knowler y Bradshaw, 2007). Además, mejora diferentes propiedades físicas, químicas o biológicas contribuyendo, por lo tanto, a la mejora de la calidad del suelo. Por ejemplo, el uso de este sistema permite aumentar la capacidad del suelo de almacenar agua útil para las plantas (Bescansa et al., 2006), o incrementar la variedad y la actividad biológica del suelo tanto encima como debajo de la superficie (FAO, 2003; Friedrich et al., 2012). Por otro lado, el laboreo es una de las actividades agrícolas que más energía consume. Es por ello que la Agricultura de Conservación permite realizar un ahorro en combustible debido a la disminución en el número de labores a realizar en comparación con el laboreo convencional (Crosson, 1982).

Sin embargo, este sistema también presenta una serie de desventajas. La realización de no laboreo o siembra directa aumenta el gasto en fitosanitarios para controlar las hierbas adventicias, que en laboreo convencional son erradicadas mediante diferentes laboreos. Se produce un aumento de la densidad aparente del suelo que conlleva una mayor compactación del mismo (Bescansa et al., 2006; Fernández-Ugalde et al., 2009). La presencia de restos de cultivos puede producir problemas de plagas y enfermedades a largo plazo. Además, estos restos de cultivo pueden dificultar la nascencia de las semillas, si no se realizan siembras cuidadosas. En el caso de siembras de primavera incluso se pueden producir retrasos en la germinación ya que dichos residuos hacen que la temperatura del suelo sea menor (Crosson, 1982). Estas razones hacen que la implantación de estas técnicas requiera un conocimiento adecuado del contexto edafoclimático y agrícola en que se desarrollan.

Distribución mundial de la AC. El efecto del laboreo sobre el suelo se empezó a cuestionar por primera vez hacia 1930 debido a la erosión eólica que arrasó grandes extensiones de terreno en Estados Unidos, pero no fue hasta 1960 que la Agricultura de Conservación se empezó a poner en práctica (Friedrich et al., 2012). En 1990 se introdujo con mucha fuerza en Brasil, y a partir de ahí se empezó a extender a otras partes del mundo, generando interés en organismos internacionales tales como la FAO. Según datos de este organismo (2003), alrededor de 125 millones de ha se manejan siguiendo esta práctica, lo que supone el 9% de la tierra cultivable (Pittelkow et al., 2015). En Europa este tipo de agricultura no está ampliamente adoptada ya que solo el 1% del total de hectáreas bajo AC se encuentran en este continente. Su introducción en España se realizó hacia 1980 respondiendo a una búsqueda de la simplificación del laboreo, al poco tiempo disponible debido a la realización de múltiples actividades, así como la necesidad de disminuir los costes (Lahmar, 2010). La superficie dedicada representa un poco menos de la mitad de la superficie total de Europa, con 650.000 ha de terreno (FAO, 2003).

Tal y como explica Friedrich et al. (2012), ese sistema se ha asociado comúnmente a secanos, pero debido a su expansión en todo tipo de suelos, podría ser perfectamente aplicado en parcelas de regadío bajo climas semiáridos.

Influencia en las propiedades del suelo y en los cultivos. La materia orgánica se ha considerado desde hace tiempo un indicador válido para evaluar un suelo. El contenido de materia orgánica varía en función de diversos factores, entre los que se encuentra el tipo de laboreo. Cuando un suelo se labra, se favorece la mineralización de la materia orgánica presente ya que se rompen los agregados del suelo que la protegen, quedando ésta desprotegida y accesible para los microorganismos. Por este motivo, la AC presenta un efecto potencial para **incrementar el carbono orgánico del suelo**, lo que podría ser interesante no sólo con el objetivo de mitigar el impacto del cambio climático, sino de aumentar la resiliencia del suelo y su potencial de producción. Sin embargo, la capacidad de secuestro de carbono de un suelo bajo AC en comparación con el laboreo convencional sigue siendo un tema controvertido objeto de numerosos estudios. La observación de diferencias entre los manejos depende de las propiedades de las diferentes zonas de estudio, de las condiciones de partida o de las condiciones de la experimentación (Ladoni et al., 2015). Además, se estima que es necesario que pase un mínimo de 5 años para que se puedan observar cambios debidos al manejo ya que el momento de mayor incremento del SOC se produce a partir de este periodo tras la conversión (West y Post, 2002; Varvel y Wilhelm, 2011). Virto et al. (2012) demostraron que incluso en estudios con más tiempo de duración, el almacenamiento de SOC asociado al no laboreo es dependiente del aumento de rendimientos asociado a este sistema frente al laboreo de inversión.

Es por ello que parece más adecuado no evaluar la capacidad productiva o de secuestro de C de un ecosistema utilizando la cantidad de materia orgánica como único indicador (Franzluebbers, 2002; Six et al., 2002). Es posible utilizar otros indicadores, tales como el grado de estratificación, ya que un mayor contenido de materia orgánica en la capa más superficial del suelo tiene un efecto vital en la función del ecosistema del suelo, la conservación de los nutrientes, las propiedades físicas y en el control de la erosión (Franzluebbers, 2002). Tal y como indican diversos autores (West y Post, 2002; Lahmar, 2010; Du et al., 2017), el incremento del SOC bajo AC se produce principalmente en la capa superficial del suelo, reduciéndose en profundidad. Esto se debe a que los residuos que quedan en superficie se descomponen más despacio que los que se introducen dentro del suelo mediante el laboreo porque son menos accesibles para los microorganismos presentes y además la humedad disponible es menor (Follet, 2001; Franzluebbers, 2002). En el laboreo convencional, los residuos son repartidos por toda la profundidad de trabajo. Además, cuando se labra el suelo se disminuye su agregación reduciendo a su vez la posibilidad de protección de la materia orgánica dentro de los mismos (Six et al., 2002; Martínez et al., 2008). Por lo tanto, aunque exista un cierto grado de estratificación tras labrar, el no laboreo induce una mayor estratificación vertical de la materia orgánica.

Otros parámetros que pueden utilizarse para indicar cómo evoluciona la calidad de un suelo, y que también se ven afectados por cambios en el manejo del mismo, son la fracción más lábil de la materia orgánica (POM), el carbono mineralizable, la relación C:N o la relación C orgánico lábil con el total (Martínez et al., 2008). La POM es una fracción de la materia orgánica comprendida entre los 0,053 y 2 mm de tamaño que representa un estado intermedio de descomposición de los residuos, y que es fácilmente descompuesta por los microorganismos. Por lo tanto, es un indicador más sensible a cambios en el manejo del suelo que la materia orgánica total ya que se ve mermado rápidamente con la labranza (Cambardella y Elliott, 1992; Six et al., 2002). En suelos semiáridos mediterráneos se ha observado que es el indicador más precoz de los cambios en la calidad del suelo asociados a cambios en el manejo (Imaz et al., 2010). Por su parte el C mineralizable es un buen indicador de fracciones activas de C ya que la tasa de CO_2 respirado refleja la disponibilidad de carbono lábil. Además, es capaz de mostrar cambios en periodos cortos de tiempo (Ladoni et al., 2015).

Un incremento de la materia orgánica del suelo bajo AC favorece la fertilidad del suelo debido a una mejora general de la **disponibilidad de los nutrientes**, así como la respuesta a los fertilizantes lo que podría ser explicado por una mejora del pH (Díaz-Zorita y Grove, 2002). Sin embargo, este efecto puede estar limitado a la capa más superficial del suelo. Por otro lado, se ha observado que en algunos estudios la cantidad de nitrógeno necesario en AC puede ser mayor, lo que se podría atribuir a una menor disponibilidad de este nutriente debido a su necesidad para la descomposición de los residuos dejados por el cultivo anterior (Rhoton, 2000; Brennan et al., 2014) Además, en AC se puede disminuir la infiltración de agua, lo que reduce las pérdidas de nutrientes y los problemas medioambientales asociados a ella (Arroyo Garcia et al., 2012).

Los estudios realizados hasta el momento indican que la práctica de la agricultura de conservación también tiene un impacto en **la estructura y la porosidad del suelo**, aunque la magnitud de los efectos depende de la textura, de las condiciones climáticas y del tipo de AC que se practique (Lahmar, 2010). La compactación del suelo y por ende la disminución de la porosidad del suelo ha sido observada en diferentes situaciones. Sin embargo, esta disminución en la porosidad se puede ver superada por un cambio en la distribución de los poros que permite aumentar la capacidad de retención de agua del suelo (Shipitalo et al., 2000; Bescansa et al., 2006; Fernández-Ugalde et al., 2009). Además, diversos estudios indican que bajo AC se puede reducir la evaporación de agua del suelo debido tanto a la presencia de los residuos de cultivo en la superficie como de las cubiertas vegetales, incrementándose de esta manera la capacidad de retención de agua del suelo (Lahmar, 2010; Verhulst et al., 2011).

El efecto que produce la Agricultura de Conservación sobre la **producción de los cultivos** es variable (Verhulst et al., 2011). Lahmar (2010) indicó que la introducción de esta práctica en Europa no ha generado un incremento de las producciones excepto en los suelos menos fértiles o durante años secos. De la misma manera Pittelkow et al. (2015) indicaron que esta práctica reduce los rendimientos, aunque bajo condiciones específicas como es la implementación de los tres principios de la agricultura de conservación al mismo tiempo (laboreo reducido, mantenimiento de cubiertas vegetales y rotaciones de cultivos), especialmente en climas secos, puede igualar o superar las producciones obtenidas con el laboreo convencional.

MARCO DE TRABAJO Y ESTRUCTURA DE LA TESIS

La presente tesis se enmarca en un proyecto de investigación que evalúa la influencia de la Agricultura de Conservación en los cultivos en regadío, financiado por el Instituto Nacional de Investigación Agraria y Agroalimentaria (INIA) dentro de su Programa Nacional de I+D+i "Subprograma Nacional de Recursos y Tecnologías Agrarias en Coordinación con las CCAA" (ref. proyecto RTA 2010-00006-C03-00). Este proyecto se enfocó en el efecto que puede ejercer la Agricultura de Conservación en combinación con las técnicas de Producción Integrada a la hora de regular las producciones de los cultivos, aumentar la rentabilidad económica de las explotaciones y favorecer la conservación de recursos naturales y medioambientales. Para abordar estos diferentes aspectos, el proyecto se estructuró en diferentes líneas de trabajo siendo la **influencia de la Agricultura de Conservación en los indicadores de calidad del suelo y la producción de los cultivos** el apartado en el que se enfoca la presente tesis.

Anteriormente, el equipo de trabajo del proyecto había observado en otros trabajos que los nutrientes, la materia orgánica y la capacidad de retención de agua del suelo se ven incrementados al utilizar sistemas de laboreo de conservación en parcelas de secano. Es por ello que se detectó la necesidad de realizar ensayos de campo para evaluar si la influencia de este sistema de laboreo sería similar en suelos convertidos a regadío. Además, en vista de que dicha conversión incluyó suelos marginales o suelos con presencia de elementos gruesos, y sumando a esto la escasez de información sobre sus efectos, se decidió ampliar la tesis con una nueva línea de trabajo que afronta este tema y que constituye el otro pilar estructural que se aborda en la presente tesis. En este sentido se vio necesario evaluar si las metodologías de estudio habitualmente utilizadas en la estimación de cambios de uso del suelo son suficientes y adecuadas cuando se evalúan suelos pedregosos. Para ello se condujeron los ensayos experimentales descritos en los capítulos II, III y IV en una parcela situada en Navarra. Además, se profundizó en el efecto que ejercen los elementos gruesos en las propiedades hidráulicas del suelo mediante una serie de ensayos experimentales llevados a cabo en el Departamento de Ciencias de las Plantas y del Suelo de la Universidad de Kentucky (USA).

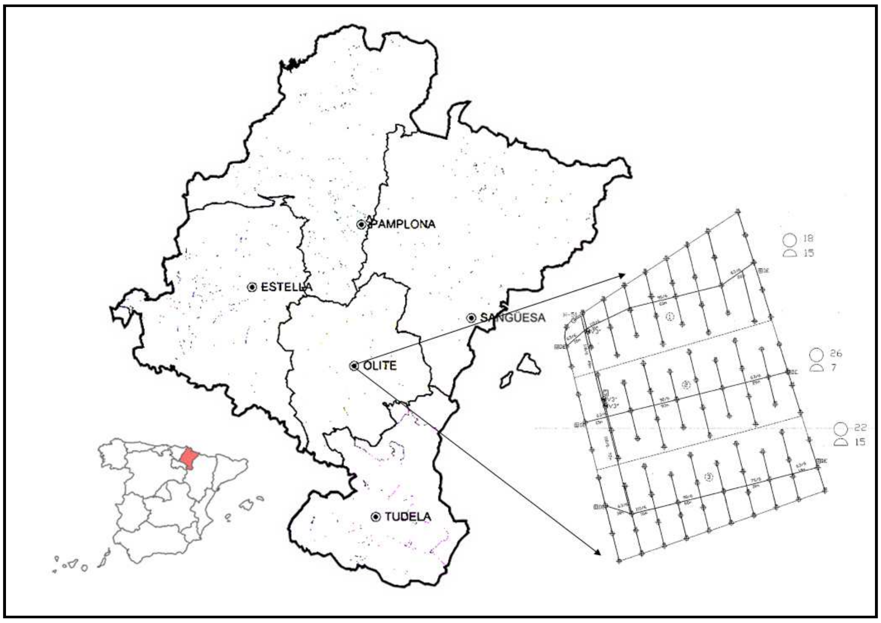

Figura 5. Mapa de Navarra y parcela de estudio.

Descripción de la zona de estudio. La parcela de ensayo se situó en el término municipal de Olite (Navarra) en el NE de España (Figura 5). El clima de la zona es Mediterráneo templado (TE Me) según la clasificación de Papadakis (1975), con veranos secos y templados. La precipitación media de la zona se sitúa alrededor de los 500 mm siendo la estación más seca el verano. En esta localidad gran parte de superficie agrícola se dedicaba al cereal y a la viña así como a otros cultivos menos relevantes antes de la introducción del regadío (Gobierno de Navarra, 2006).

La unidad de suelo en la que se sitúa la parcela se caracteriza por formar parte de un dispositivo general de terrazas colgadas, con un contacto muy claro con los materiales subyacentes. Estas terrazas son definidas como cantos y gravas de caliza y cuarcita, mayoritariamente con matriz arenosa de color pardo rojizo. No suelen alcanzar un elevado desarrollo superficial y están dispuestas de manera que dan una serie de plataformas escalonadas paralelas al cauce principal (Gobierno de Navarra, 1993). El suelo de la parcela de ensayo se clasifica como *Petrocalcic Calcixerept* (Soil Survey Staff, 2014). Es un suelo superficial que presenta un horizonte petrocálcico a unos 30-35 cm de profundidad (Figura 6). Como es característico de estas terrazas, el suelo presenta un alto contenido en elementos gruesos, siendo el tamaño más abundante el que corresponde a la fracción comprendida entre los 20 y 60 mm, denominada como *gravas* según FAO (2006). La mayoría son areniscas de diferentes tipos (verdosas, rojizas y blanquecinas). Suelen estar rodeadas de una capa de carbonato cálcico. También hay fragmentos del horizonte cementado (caliche) y conglomerados polimícticos, aunque estos con menor presencia.

Figura 6. Detalle de los perfiles excavados en la parcela experimental.

Diseño experimental y manejo. El diseño experimental fue un split-plot con tres repeticiones ajustado a un sistema de riego por aspersión de 15x18 m con tres sectores de riego independientes (Figura 5). Estos sectores siguieron una rotación de cultivos de maíz (*Zea mays* L.), trigo (*Triticum aestivum* L.) y sorgo (*Sorghum vulgare* L.).

Los sistemas de laboreo realizados fueron dos. Por un lado, el laboreo convencional (CT) que consistió en una labor profunda de chisel a una profundidad de unos 15 cm y posteriores labores secundarias con cultivador hasta siembra. Por otro lado, se realizó un no laboreo (NT) que consistió en la siembra directa sobre los residuos del cultivo anterior (Figura 7). El primer año del proyecto, referido como año 0, se realizó la misma labor por toda la parcela para evitar heterogeneidades debidas al manejo previo. Durante el segundo año del proyecto (año 1), las parcelas del sector de riego 1 recibieron dos pases superficiales de chisel y un cultivador (3-4 cm) para poder controlar la proliferación de hierbas que se produjo ese año debido a las altas lluvias de otoño. Asimismo, en las parcelas de no laboreo del sector 2 se realizó un pase de molón para facilitar la siembra. En el tercer año del proyecto (año 2), el laboreo se realizó sin ninguna incidencia.

La fecha, variedad y dosis de siembra de los cultivos durante los diferentes años de estudio puede observarse en la Tabla 1.

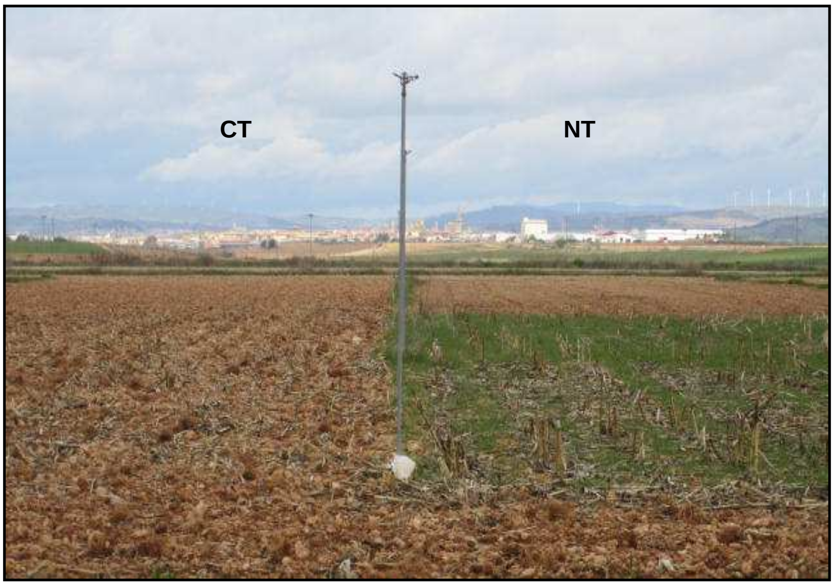

Figura 7. Detalle de los diferentes sistemas de laboreo empleados en la parcela, no laboreo (NT) y laboreo convencional (CT).

La aplicación de abono nitrogenado se dividió en dos dosis diferenciadas. Con la dosis de fertilización convencional de la zona (F1) se aplicaron 150 Unidades Fertilizantes de Nitrógeno (UFN) en trigo y 300 UFN en maíz y sorgo. Sin embargo, con la dosis de fertilización siguiendo las normas de producción integrada de cada cultivo (F2), se aplicaron 120 UFN en trigo y 250 UFN en maíz y sorgo. Por otro lado, todos los cultivos y parcelas recibieron un abonado de fondo con fósforo a una dosis de 70 kg/ha.

El tratamiento de la flora adventicia se realizó mediante el uso de productos fitosanitarios.

Las dosis de agua de riego y el calendario se calcularon en función de las necesidades hídricas del cultivo, determinadas sobre la base de los datos meteorológicos según la fórmula de cálculo de Penman-Monteith facilitadas por el servicio de asesoramiento al regante de INTIA.

Tabla 1. Fecha, variedad y dosis de siembra de los diferentes cultivos del ensayo experimental.

	Año	Variedad	Fecha siembra	Dosis
Trigo	0	Arthur Nick	01-02-11	258 kg/ha
	1	Berdún	14-11-11	250 kg/ha
	2	Sensas	12-12-12	240 kg/ha
Maíz	0	PR34N84	11-05-11	80.000 plantas/ha
	1	LG3490	17-05-12	80.000 plantas/ha
	2	LG3490	16-05-13	80.000 plantas/ha
Sorgo	0	Néctar	11-05-11	11 kg/ha
	1	Néctar	17-05-12	13 kg/ha
	2	Néctar	13-05-13	13 kg/ha

Figura 8. Detalle de la toma de muestras de suelo (a y b). Detalle de la separación de elementos gruesos de la tierra fina (c y d)

Estructura de la tesis. Según lo explicado anteriormente, la tesis está organizada en los siguientes capítulos: el capítulo I recopila los factores fundamentales bajo los que se enmarca la tesis y los objetivos que se han establecido en la misma. En los capítulos centrales II, III, IV y V se realizan diferentes trabajos de investigación para testar las hipótesis planteadas con respecto a la Agricultura de Conservación en regadío y el efecto de la presencia de fragmentos de roca. Específicamente, en el capítulo II se recogen los conceptos clave necesarios para la descripción y cuantificación de los elementos gruesos (Figura 8).

Figura 9. Análisis de la materia orgánica en laboratorio (a); Muestras para el análisis de la curva de retención de agua (b); Detalle experimento de la dinámica de secado en campo bajo no laboreo con el suelo sin cubrir (c) y cubierto (d).

El capítulo III está enfocado al estudio del efecto de la Agricultura de Conservación en diferentes propiedades físicas y químicas del suelo (Figura 9 a). El capítulo IV se centra en las implicaciones de utilizar una metodología adecuada en las estimaciones de cambios en la materia orgánica, en los indicadores de calidad y en los stocks de carbono debidos al manejo cuando se realiza en suelos pedregosos (Figuras 9b, 9c y 9d). La influencia que ejerce la presencia de fragmentos de roca en la curva de retención de agua del suelo y en la conductividad hidráulica insaturada son evaluados en el capítulo V (Figura 10). Por último, en el capítulo VI, se discuten en conjunto los resultados de los diferentes capítulos, que se resumen en las conclusiones generales.

Figura 10. Detalle columnas de suelo para la evaluación de las propiedades hidráulicas.

OBJETIVOS DE LA TESIS

El objetivo general de esta tesis es evaluar la influencia de la Agricultura de Conservación en una parcela pedregosa en regadío y estudiar cuál es el papel de los fragmentos de roca presentes en el estudio de las propiedades del suelo. Con este fin, se plantean los siguientes objetivos específicos, que se desarrollan en los diferentes capítulos:

1. Revisar los aspectos más importantes en la descripción y cuantificación de la pedregosidad desde el punto de vista de la Ciencia del Suelo, evaluándolos en la parcela de estudio.

2. Estudiar el efecto del no laboreo en comparación con el laboreo convencional de la zona con respecto a la producción de cultivos, la disponibilidad de nutrientes y su interacción con la optimización del nitrógeno, la materia orgánica, y sobre la capacidad de retención de agua del suelo y su dinámica de movimiento.

3. Estudiar las implicaciones de la metodología empleada para estimar el efecto de los cambios del manejo del suelo cuando existen fragmentos de piedras en los resultados referidos a la tierra fina, en la idoneidad de los indicadores de calidad y en el cálculo de stocks de carbono de este tipo de suelos.

4. Determinar el efecto de la pedregosidad en los parámetros hidráulicos del suelo y la idoneidad de la metodología empleada para obtener estos parámetros a partir de la fracción fina del suelo.

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Chapter II

Methodological considerations in the study of stoniness

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ABSTRACT

The relative volume of rock fragments in a soil is called stoniness. It has a great influence on many soil parameters such as physical, thermal, or chemical properties. However, the role of the coarse fraction on soil properties, and its influence on soil functioning, has received little attention. The aim of this chapter was to give a complete overview of the most important features for rock fragments quantification, and for the interpretation of its relevance in soil functioning. An extensive review of rock fragments classification systems was first conducted. When assessing the content of rock fragments in a soil it is important to refer their size or name to the specific classification system used due to discrepancies between them. Then, a review of different methodological issues related to soil stoniness determination was conducted. It considered three aspects: (i) sampling strategies, (ii) the usefulness of geostatistical approaches, and (iii) indirect tools for stoniness estimation. For (i) and (ii) an experiment on a stony soil located in an experimental field including two tillage treatments (no-till and conventional tillage) was used. Results indicated that the use of an Edelman type auger underestimated the coarse fraction volume around 50-60% of its true value. A correct quantification was only achieved when a representative elementary volume (REV) of the soil was sampled. Geostatistical analyses were proven useful for assessing the adequacy of the sampling scheme showing that sampling intervals in the field experiment could be performed at larger intervals than 15 m. Two years of no-tillage did not affect the presence of rock fragments at the soil surface, indicating no effect of conventional tillage in changing coarse fragments distribution or inducing fine earth migration downwards in the soil profile.

For (iii) a collection of photographs from different stony soils profiles in N Spain was used for assessing the validity of two different automatized image processing methods. The results indicated that the automation of the rock fragment coverage estimation needs further development for decreasing differences (which were up to 10% in soils with rock fragments coverage lower than 20%) with the reference method. Nevertheless, it seems clear that certain recommendation should be followed when taking pictures like avoiding shadows, plastic or crop residues, soils recently ploughed or soils with a matrix of a similar colour to rock fragments.

INTRODUCTION

Soils are composed of mineral and organic materials. Much of this mineral material is inert and derived from rocks that have suffered different weathering processes including chemical and physical changes (Lal and Shukla, 2004).

Stoniness is defined as the relative volume or rock fragments in a soil. It reflects the geological origin and the status of pedogenesis development (FAO, 2006). Furthermore, it has an influence on many soil parameters such as bulk density, thermal, chemical, physical, and hydraulic properties and it also affects the soil susceptibility to erosion and the ability for plant rooting. The rock fragments of a soil may show a heterogeneous distribution through the profile, concentrated in the mpared to a methodology that is being developed at the Public University of Navarra. In this new approach, image processing was carried out by using an experimental logarithm that consists on group

In many arid and semiarid areas or areas where fluvial and glacier processes have contributed to soil formation, stoniness is abundant (Fernández, 2003). In addition, the use of soils with high amounts of rock fragments for food and fibber production is an extended practice (Poesen and Lavee, 1994). However, much more attention has been paid to the study of the fine earth (particles < 2 mm) in comparison with the coarser fraction (Poesen and Lavee, 1994). In fact, in many cases the influence of stones in the soil behaviour has been ignored (Cobertera, 1993).

In areas with frequent soil fragments, it is therefore of vital importance to quantify stoniness to identify its possible implications prior to analyzing the soil response to different factors. For example, many soil properties determined on the fine earth need a correction by the stoniness content before being correctly interpreted. Also, the use of special procedures to determine some soil physical properties is necessary in some cases in stony soils (Lal and Shukla, 2004). Moreover, a specific analysis of the rock fragments seems necessary because many studies and policies are based on the up-scaling of soil properties, and the correct assessment of this characteristic may imply fewer estimation errors when using results of studies conducted at the plot scale for local or regional assessments

The objective of this chapter is to give an overview of the analysis of rock fragments in soil science and the importance of their adequate quantification in soil quality studies. This was conducted in a step-wise process. First, a revision of the different criteria existing for coarse fragments classification was conducted to study the differences among the most widespread systems. Second, the significance of an adequate methodology for their quantification was studied in three aspects: (i) soil sampling strategies, (ii) geostatistical tools to evaluate coarse fragments distribution and the influence of tillage by conducting a study in an experimental field, and (iii) image analysis techniques for indirect estimation of soil stoniness by comparing two methodologies on a collection of photographs of stony soils in N Spain.

STONINESS DESCRIPTION

Rock fragments classification. Soil mineral particles can be described in very different ways attending to mineralogical, shape or volume criteria. One of the most used to define this soil fraction is the size. By convention, mineral particles <2 mm in equivalent diameter (clay, silt, and sand) are considered as the *fine earth* and, depending on their proportion, they constitute the different soil texture classes. Mineral particles > 2 mm are defined as rock fragments constituting the coarse fraction of the soil (Cobertera, 1993).

A rock or coarse fragment can therefore be defined as “an unattached piece of rock 2 mm in diameter or larger that is strongly cemented or more resistant to rupture” and include all those sizes which have smaller horizontal dimensions than the size of a pedon (Soil Survey Division Staff, 1993). It includes different classes like pebbles, cobbles, stones, and boulders.

Depending on the soil classification system, rock fragments are named differently according to their size. Schoeneberg et al. (2002) made a comparison that is depicted in Figure 1.

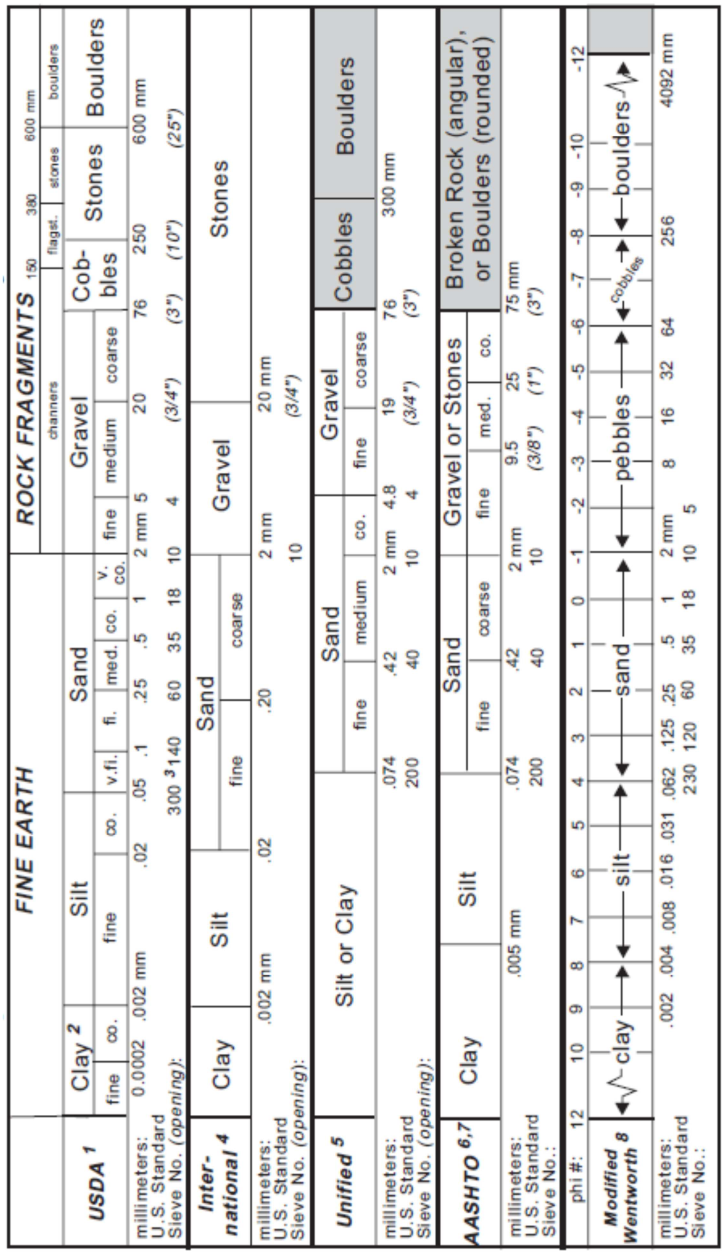

Figure 1. Comparison of Particle Size Classes in Different Systems according to Schoneberg et al. (2002).

As this figure shows, the USDA classification system considers as *stones* those rock fragments from 250 mm to 600 mm of diameter. On the contrary, the International classification system (Soil Survey Staff, 1951) contemplated *stones* as those rock fragments with a diameter > 20 mm. On the other hand, FAO classification (FAO, 2006) names as *gravels* those rock fragments with sizes from 2 to 60 mm and as *stones* rock fragments between 60 mm and 200 mm in size. Therefore, from a general perspective, it seems preferable to use *rock fragments* as a more general nomenclature to refer to the soil coarse fraction instead of *stones* (Andrades et al., 2007) or specify the classification system used.

Besides this, rock fragments can be described attending to their roundness and sphericity (shape), which is more commonly used in geologic and engineering purposes, their nature, or the degree of weathering (Soil Survey Division Staff, 1993; FAO, 2006). Figure 2 shows the different classes existing in these categories.

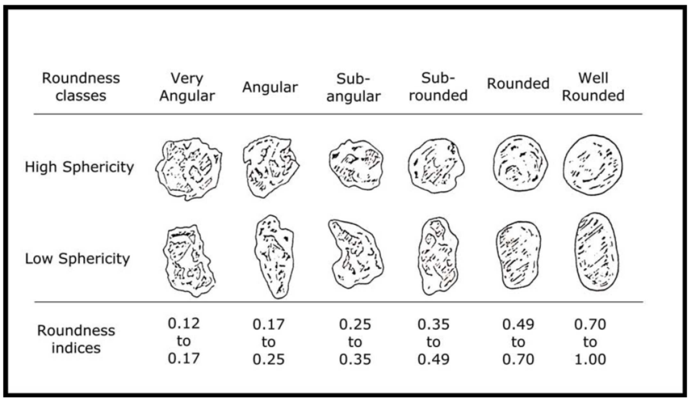

Figure 2. Classification of rock fragments according to their shape (modified from Powers, 1953).

Classification and evaluation of soils containing rock fragments. The volume occupied by rock fragments in a soil is used in soil classification for identifying and naming soil units. For this purpose, "rock fragment texture modifiers" are used as adjectives added to soil texture for describing the characteristic stoniness of a soil. These modifiers refer to the percentage volume of rock fragments, as described by Schoeneberg et al. (2002) in Table 1. When soils contain more than 35% rock fragments, they are also identified as “skeletal” soils in the Soil Taxonomy (Lal and Shukla, 2004) although FAO (2006) established the boundary for this term at 40%.

In addition, land evaluation systems such as those designed for arable lands also consider criteria for soils qualification depending on their rock fragments content, because of the effect that rock fragments have on cultivation, which is for example more accentuated than the effect they exert on forestry (Soil Survey Division Staff, 1993). This is the case of rock fragments at the soil surface because not only they affect the potential use of soils, but also, they can limit their management by impeding tillage or crop development.

Table 1. Textural adjectives for describing the content of rock fragments in a soil (Schoeneberg et al., 2002).

Rock fragment content by volume (%)	Rock fragment modifier usage
< 15	No texture class modifier is used
15 to < 35	Use adjective for appropriate size; e.g. *stony*
35 to < 60	Use “very” with the appropriate size adjective; e.g. *very stony*
60 to < 90	Use “extremely” with the appropriate size adjective; e.g. *extremely stony*
≥ 90	No adjective or modifier. If ≤ 10% fine earth, use the appropriate noun for dominant size class; e.g. *stones.* Use terms in lieu of texture

This stoniness at the topsoil layer can be described by its gravimetric content, its volumetric content or visually, attending to rock fragments size and percentage of land covered (Lal and Shukla, 2004). Usually, six soil classes are identified according to the rock fragments surface cover and the distance between them. But also in this case criteria between classification systems differ. For example, USDA uses stones larger than 250 mm. Porta and Lopez-Acebedo (2005) combined information from USDA and FAO and described the criteria for the rock fragments cover classification together with its effects on soil management. This information is described in Table 2.

Table 2. Criteria for surface soil stoniness and its effect on soil management (Porta and Lopez-Acebedo, 2005).

Class	% of surface covered by rock fragments	Distance (m) between rock fragments	Effects	Description
Criteria related to surface rock fragments from 150 - 300 mm				
0	< 0.01%	-	Stones do not affect management	Not stony
1	0.01 - 0.1	10 - 30	Stones interfere with tillage insignificantly	Slightly Stony
2	0.1 - 3.0	2 - 10	Stones have influence on tillage	Moderately stony
3	3.0 - 15	1 - 2	Enough stones to impede the use of machinery except light and manual	Very stony
4	15 - 30	0.7 - 1.5	Impossible to use machinery	Excessively stony
5	30 – 90	> 0.7	Soil cannot be cultivated	Extremely stony
Criteria related to surface rock fragments from 10 - 150 mm				
1	< 10	-	There are not interferences	Not much gravelly
2	10 – 30	-	Moderated difficulties for some till operations like sowing	Medium content of gravels
3	30 – 70	-	Higher interference with tillage	Lots of gravels
4	> 70	-	Soil covered by gravels	Extremely gravelly

However, if the criterion used for assessing surface stoniness is only the percentage of rock fragments in volume, the classification varies (Porta and Lopez-Acebedo, 2005):

1. No stoniness: < 1%
2. Very light surface stoniness: 1 - 5%
3. Light surface stoniness: 6 - 15%
4. Moderate surface stoniness: 16 - 35%
5. A lot of stoniness: 36 - 70%
6. Excessive stoniness: > 70%

These different observations indicate that although there is general agreement that rock fragments can interfere with soil functioning to the point of affecting its inherent characteristics and their aptitude for different purposes, the relationship between rock fragments abundance and characteristics and therefore these limitations, is not straightforward. Careful attention has to be paid to stoniness at a local scale when studying soils and their interaction with management strategies.

METHODOLOGICAL CONSIDERATIONS FOR STUDYING SOIL STONINESS

One of the major issues to be considered when facing the study of stony soils is the determination of their mass and volume content, as well as their spatial distribution in the soil. Two aspects are significant: the accurate determination of the quantitative proportion of rock samples to the total soil mass and volume, and the determination of their distribution in the soil both in depth and at the surface level. In this chapter, three studies were conducted to gain knowledge in these two aspects. First, in an experimental plot designed to test the effect of no-tillage (NT) and conventional tillage (CT) on soil properties, an experiment was conducted to test the efficiency of two sampling methods (digging vs. auger) for the determination of total soil stoniness. Second, on the same experimental field, a geostatistical analysis was conducted to evaluate the spatial distribution of stones and the potential effect of tillage in rock fragments re-distribution.

The methodology used for estimating field stoniness depends on the objective of the study and the precision required (Hodgson, 1987). In addition to direct methods like the ones described above, non-destructive or indirect methods have also been developed. A review of indirect methods currently available was done and a collection of samples from different soil profiles in N Spain was used to compare two methods of image analysis. The following sections describe these studies.

Key aspects for soil sampling. The characterization of rock fragments present in a soil is not a simple matter. Usually, the procedures used for their estimation are direct determinations by soil sampling.

One of the most important things when a soil is to be sampled for stoniness quantification is to sample a representative elementary volume (REV) (Bear, 1972). The variability among replicate samples tends to increase as sample volume decreases (Lauren et al., 1988). Therefore, if the soil sample does not contain a representative portion of rock fragments, it may constitute a source of error (Butcher et al., 1994; Muller and Hamilton, 1992; Auerswald and Schimmack, 2000). There is not a strict rule on how to evaluate the REV on a soil and its dimensions could vary from centimetres to meters (Hlaváciková and Novák, 2014). Therefore, the adequate REV to be used when measuring the hydrophysical characteristics of soil with rock fragments depends on the size of the latter. Butcher et al. (1994) recommended a dry mass soil sample being at least 100 times the mass of the largest rock fragment. On the other hand, Novák et al (2011) and Novák and Knava (2012) suggested that soil samples from stony soils should contain at least 20 rock fragments and the volume for this determination should be higher that the volume of the Kopecky cylinder, 100 cm^3.

On the other hand, in soils that contain rock fragments it is very problematic to conduct determinations that require the extraction of intact clods. The high amount of rock fragments or their size may interfere with the extraction by impeding it or by creating voids where rock fragments are moved away (Muller and Hamilton, 1992). This is especially relevant when measuring bulk density or hydraulic soil properties but it is also important for accurate determinations of the rock fragment content.

In order to assess the accuracy of different sampling strategies, an experimental field located in the Ebro river basin with a high content in rock fragments was analysed. The soil, gravelly (FAO, 2006) and with a sandy-clay loam texture, was classified as a *Petrocalcic Calcixerept* (Soil Survey Staff, 2014). Soil samples were collected from 36 data points at 0-5 cm, 5-15 cm, and 15-30 cm depth. Two different methods were used for obtaining soil samples. On the one hand soil was collected by using an Edelman type auger. On the other hand, soil pits were dig and an extensive volume of soil was collected from each location. The mass of the rock fragments was then quantified for both methodologies, and the difference between both practices was analysed for determining significant differences based on a probability level of p < 0.05. The statistical analyses were performed using the SPSS 18.0 software (SPSS Inc., 2009).

Table 3. Rock fragment by mass obtained by digging a pit and by using an Edelman type auger and their difference in percentage.

	Digging pit sampling (%)		**Edelman type auger sampling (%)**		**Underestimated rock fragment content (%)**	
Depth (cm)	Mean	Error	Mean	Error	Mean	Error
0 - 5	60.93a	1.64	23.41b	2.05	59.51	3.89
5 - 15	46.52a	1.38	20.51b	1.10	55.23	2.39
15 - 30	45.24a	1.26	20.27b	0.67	53.89	2.06

Different letters indicate significant differences (p < 0.05) between methodologies for the same depth (n=36).

Table 3 shows the mean and standard error values obtained from this experiment. The coarse fraction contents of the soil collected by the Edelman type auger were significantly lower than those collected by digging pits for all depths studied. Similar results were also reported by Muller and Hamilton (1992). The percentage of rock fragments that was underestimated by the Edelman type auger sampling was around 50-60% for all depths studied (Table 3) even though the most abundant proportion of rock fragments were gravels (< 60 mm) (FAO, 2006) and bigger fragments (stones or boulders) were not present. The explanation relays on the size of the steering auger limiting the size of rock fragments collected (Throop et al., 2012) together with the limitations of this methodology for sampling a REV.

Therefore, in soils that contain rock fragments the need for excavating a REV for adequate quantification of rock fragments has to be considered for, and this implies that conventional methods for sampling non-stony soils are often not adequate.

Finally, it has to be said in relation to sampling that another source of error when quantifying rock fragments can be the incomplete separation of fine earth from the rock fragments (Auerswald and Schimmack, 2000). Separating soil particles by sieving using a mash of 2 mm is sometimes not enough because fine earth attached to rock fragments cannot be adequately separated only by sieving. In these cases, samples should be disaggregated prior to sieving for example by immersing them in a sodium hexametafosphate solution. This procedure grants complete detachment of fine particles from coarse fragments, but impedes further analysis of the fine earth as such. A compromise needs to be reached if both fractions are needed for analysis. Excavation allows for collecting samples that could be split into two twin sub-samples able to be used for fine earth and coarse fragment analyses.

Geostatistical tools for studying stoniness heterogeneity. Rock fragments in a soil may adopt a very heterogeneous distribution. They can be concentrated vertically through the soil profile or laterally at the soil surface. This lateral rock fragment concentration can be caused by removal of the fine earth and/or upward migration of rock fragments (Poesen and Lavee, 1994). Tillage can have an influence in these processes, as it mixes up the tilled layer, and also favours erosion and fine earth migration compared to natural or non-tilled conditions.

A common statistical approach was used to study the influence of tillage on rock fragment content in the field described above. Two tillage treatments were compared. Conventional tillage (CT) consisted on various chisel-ploughing operations to a depth of 15 cm that incorporated crop residues into the soil, followed by seedbed preparation using a cultivator. No-till (NT) consisted on direct seeding maintaining crop residues on the soil surface. Analysis were conducted two years after NT system was initiated in the field at the 0-5 cm, 5-15 cm and 15-30 cm depths.

Table 4 shows that the rock fragment content (by mass) for the different tillage treatments evaluated was not different between tillage treatments, but varied with depth homogeneously.

Table 4. Rock fragment by mass per tillage treatment and depth.

	Rock fragment content (g 100 g^{-1})		
	0-5 cm	5-15 cm	15-30 cm
CT	60.70a ± 2.22	46.24a ± 1.63	45.27a ± 2.02
NT	61.16a ± 2.49	46.79a ± 2.27	45.21a ± 1.55

Different letters indicate significant differences ($p < 0.05$) between tillage treatments.

There was a greater proportion of rock fragments in the upper five centimetres of the soil (61 %) compared to the layers below (45-46 %) for both treatments. Some authors have described tillage as responsible for coarse fragments accumulation at the soil surface, in as short periods of time as two tillage operations (Poesen and Lavee 1994; Wijdenes et al. 1997). Our work cannot determine if the observed stratification of stones in the studied soil is the result of historical tilling before the experiment started, or a natural characteristic of this soil. We, however, did not observe any difference due to the use of CT, which could have moved rock fragments from the upper horizon downwards distributing them homogenously throughout the soil profile, in the time since the study started. This could be due to CT not including mouldboard-ploughing.

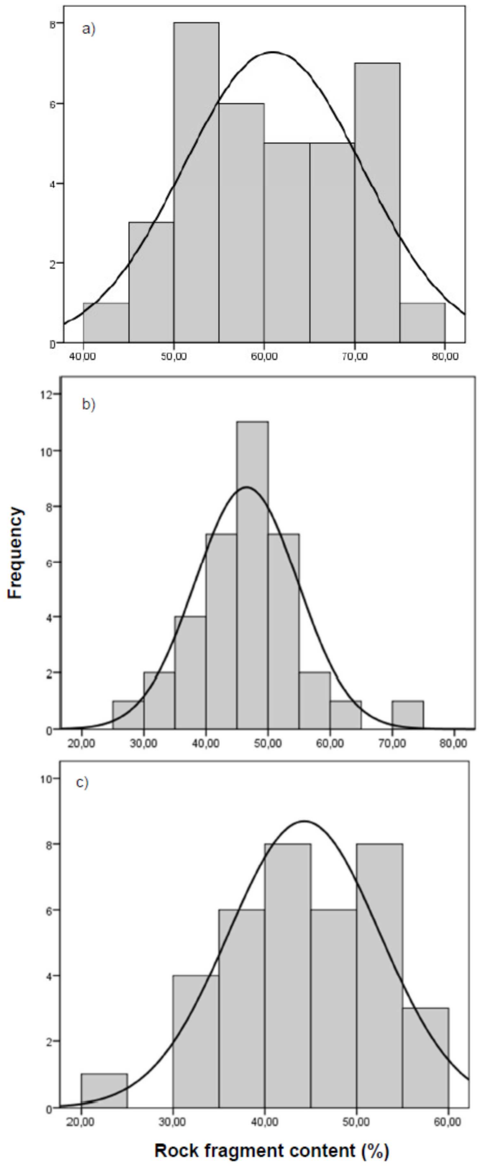

Figure 3. Histogram of rock fragment content for a) depth 0-5 cm; b) depth 5-15 cm; c) depth 15-30 cm.

In addition, and in relation to the sampling strategies described above, the assessment of the spatial distribution of rock fragments when stoniness is very variable or heterogeneous spatially is also needed to assure that the content of stones is representative of the area where soil is to be sampled. Therefore, one of the first steps when analysing a soil is to define homogeneous areas depending on the field characteristics.

Geostatistical analysis is a useful tool to determine the adequacy and representativeness of the sample in order to avoid biased results because of a heterogeneous distribution of rock fragments or gradients. A geostatistical analysis was conducted in the same field described above by using the Geostatistical software SGeMS v2.1 (Remy et al., 2004). To this end, first of all, the analysis of rock fragments to check whether this data followed the normal distribution was carried out. The histogram for the different depths is depicted in Figure 3. From this figure, it is possible to see that rock fragment content (%) distribution did not deviate from normality in any of the depths studied, which was confirmed statistically.

Field samples were then used to construct the semivariogram for the different depths as described by Nielsen and Wendroth (2003). The data was collected from a regular grid at 15 cm interval in six different transects yielding a total of 36 samples for every depth studied. The data was fitted to the Spherical model:

$$\gamma(h)=\begin{cases} c\cdot\left(1.5\left(\frac{h}{a}\right)-0.5\left(\frac{h}{a}\right)^3\right) & \text{if } h\leq a \\ c & \text{otherwise} \end{cases}$$

where *γ(h)* is the semivariance; *h* represents lag distance; *a* is the range and *c* is the sill. The semivariograms, despite being a little bit noisy (Figure 4), produced very useful information.

The geostatistical analysis revealed a small nugget variance (10 kg 100 kg^{-1}) for all depths studied. This indicated that the rock fragment content of samples 15 m apart was similar or within a range of 10% of variance. As reported by Auerswald and Schimmack (2000), a difference of this magnitude in rock fragment may be considered as acceptable.

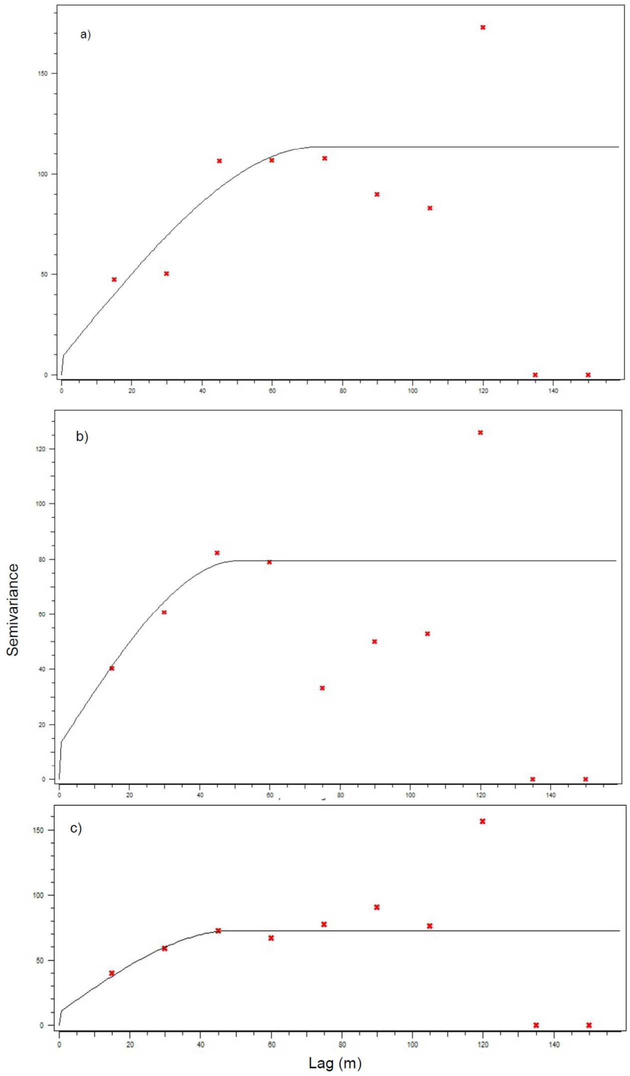

Figure 4. Experimental semivariogram of rock fragment content a) depth 0-5 cm; b) depth 5-15 cm; c) 15-30 cm.

The semivariance was higher at the upper soil layer whilst the 15-30 cm depth reached the lowest value, having, therefore, a more homogeneous distribution. In addition, Figure 4 shows that the range was achieved at 55 m for the 0-5 cm depth while at deeper layers the range was reached at 45 m. At these distances, the full scope of variability is included. Therefore, soil sampling for rock fragment quantification could be done in this soil at larger intervals than 15 m, which could reduce the cost of the field sampling without risking its reliability (Cichota et al., 2006).

Finally, the range and the sill of the semivariogram did not change in any direction (data not showed) indicating that the spatial distribution of rock fragments was the same in all directions not showing evidence of anisotropy.

To complement this information, the relation between rock fragment contents with depth was studied. An analysis of the correlation was carried out and results are shown in Table 5. The rock fragment contents at the different depths seemed to be positively related, showing a higher correlation between 0-5 cm and 5-15 cm depths. Therefore, with this vertical distribution of rock fragments with depth could be interesting to use the mass content at the upper soil layer to infer the content at deeper ones.

Table 5. Matrix of correlations for the rock fragment content at the different depths.

		Depth 0-5 cm	Depth 5-15 cm
Depth 5-15 cm	Pearson´s correlation	.549*	
	Signification	0.000	
Depth 15-30 cm	Pearson´s correlation	.315*	.362*
	Signification	0.031	0.015

* Significant value at $p < 0.05$

Indirect methodologies for estimating soil stoniness. As explained above, the proportion of rock fragments present in a soil can be expressed by volume (R_v) or by mass (R_m, as described by Poesen and Lavee (1994). The conversion of mass to volume percentage is carried out by the following equation:

$$R_v = R_m \times \frac{BD_t}{BD_{rf}}$$

where BD_t is the total soil bulk density and BD_t is the density of the rock fragments. When BD_t is not measured, it is possible to use values comprehended between 2.65 and 2.75 g/cm^3 for non-porous materials. Besides, the relative amount of rock fragments present in the topsoil can be expressed also by using the coverage of the soil surface by rock fragments (R_e).

The quantification of the volumetric content of rock fragments by digging pits is labour-intensive, time-consuming (Eriksson and Holmgren, 1996; Andrades et al., 2007; Stendahl et al., 2009; Rytter, 2012) and, as described above, it is not simple. In addition, it implies the destruction of samples. Non-destructive indirect methods, in which plots are not damaged, may be desirable especially in certain situations such as ecosystem studies (Stendahl et al., 2009). This is why there is a growing interest in developing different methodologies to estimate the rock fragment content by indirect measurements. References in literature are found for these alternative approaches. A summary of these methods follows:

1. Rod penetration technique. A thin metal rod is driven through the soil profile, to a predetermined maximum depth, until it encounters a rock fragment, moment at which it is stopped. A reference function correlates the average penetration depth of the rod with the relative volume of rock fragments present. This methodology has been validated for forest soils with elevated stoniness but not much information is available for the validation of this methodology on arable soils or on those with lower percentages of stoniness. However, rock fragments situated under others located closer to the surface may be neglected, which constitutes a source of error. This technique also assumes that small rock fragments < 20 mm are not able to stop the rod and therefore, are underestimated (Eriksson and Holmgren, 1996; Rytter, 2012).

2. Electrical resistivity tomography (ERT). It is a technique that is under development. It is based on the assumption that rock fragments are capable of affecting the electrical resistivity signal of the soil. For its adequate functioning, it is required to assure a good contact between the soil and the electrodes in order to facilitate the electrical current being injected directly on the soil. Otherwise errors may be produced. It is a methodology more adapted to soils with more than 15% of rock fragments (Tetegan et al., 2012).

3. Synthetic Aperture Radar (SAR). It is a technique that creates two or three dimensional images of objects. It was used to estimate the surface roughness and the stone cover in burnt soils with a rate of success around 70%. However, this methodology was only able to differentiate between three rock fragments classes: low content, medium content, and total cover (Menéndez Duarte et al., 2008).

4. Positive gamma-ray spectrometry. This method was used by Priori et al. (2014) to predict soil textural data as well as the relative volume of rock fragments. Results for the coverage of rock fragments show high levels of error because of their heterogeneities and different mineralogies.

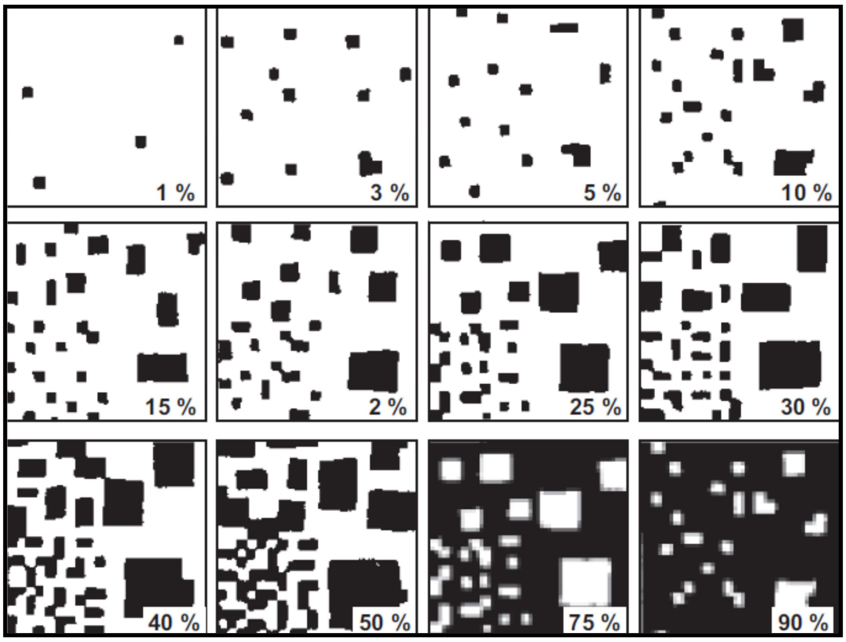

Figure 5. Chart for visual estimation of rock fragments by FAO (2006).

5. Aerial photographs. In this technique, an aerial photograph is taken and the frequency of stones and boulders at the soil surface is recorded. The inconvenience of this methodology is the higher level of error (Stendahl et al., 2009).

6. Texture charts. The estimation of rock fragments is based on the extrapolation of information from texture charts. The essential requirement is to have information of genesis and parent material (Stendahl et al., 2009).

***7. Visual estimation**.* This technique has been used for assessing rock fragment content at soil profiles from soil pits but also as the reference method for surface coverage. It is carried out with the aid of charts that show different percentages of black and white coverage like the one in Figure 5 (FAO, 2006) and also by Munsell's charts used for studying soil colour (Hodgson, 1987). The precision of this technique is very dependent on the operator's skills and expertise (Hodgson, 1987). Besides, rock fragments of low diameters may be underestimated (Stendahl et al., 2009; Tetegan et al., 2012).

In addition, when rock fragments are larger than 76 mm of diameter, the estimation of rock fragment coverage at the topsoil could be used to determine its volume content, but this becomes difficult and/or inaccurate for smaller fragments (Poesen and Lavee, 1994).

Digitised photographs for automatizing the visual estimation. In order to decrease the dependency of rock fragments visual estimation on operator skills, the systematization of these estimations has been proposed, and different methodological approaches have been developed. Image analyses of different types are among them. A study was conducted to test the efficiency of different approaches for image analysis, one mostly based on manual individual analysis and the others based on an automatized protocol. Images from different stony soils in N Spain were used. In the following sections, the setup and results of this study are shown.

1. Preliminary issues: When using photographs for defining the quantity of rock fragments present in a soil, it is important to mention that the scale used in the photographs should include all the surface necessary for an adequate quantification. This means that if the area studied is not homogeneous, similarly to soil sampling analysis, it would be necessary to analyse a representative number of images from the same area for accurate determinations.

2. *Images used*: To better evaluate the accuracy of both methods, images from both soil surface and topsoil horizons were used. To that end, a collection of images taken from all over the region of Navarra and other areas in N Spain during soil profile analysis were used for this study. In addition, a series of pictures from topsoil layers were also collected. Images selected met an important set of criteria:

- Soil surface had to be cleaned from plants, weeds, or any other interference different from soil or rock fragments (e.g., plastic residues).
- A longitudinal element of known size had to be placed on the soil surface as a reference for the pictures' scale.
- Photographs were taken with a camera that was horizontally positioned with regard to the soil surface and located in a way that shadows caused by daylight were avoided.

3. Methodology: Firstly, images were visually classified according to their content of rock fragments. This was estimated following the visual estimation technique described above by using FAO charts (Figure 5). The values obtained were used as the reference data. A selected set of images went through the process described next, including two methodologies for image analysis:

3.1. The use of soil images has commonly been successfully used during the last years for soil micromorphology analysis (Maragos et al., 2004; Lima et al., 2006; Rasa et al., 2012; Bryk, 2016). Therefore, a procedure similar to that used in Virto et al. (2013) for the quantification of porosity in soil thin sections was tested to quantify the rock fragments content in soil images.

Image analysis was performed using the free software UTHSCSA Image Tool 3.0. designed by the Texas University. Colour images are represented by the RGB system. Therefore, the first step was to split the original image into the three RGB channels. Not much difference in contrast was found between channels but the Green channel was selected from the rest of the images and was used for analyses.

The next stage in image processing was the segmentation. It consists on transforming images to a grey scale in order to obtain binary images. This task is very important in soil analysis for detecting and recognizing objects from the background (Maragos et al., 2004; Qiao et al., 2006;).

After segmentation, images were thresholded manually to obtain black & white images in which rock fragments would appear black and the rest of the image, white. The threshold level (the limit value of grey level between the fine earth and rock fragments) was based on the histogram that represents the abundance of every grey level on the image. This methodology assumes that the image is divided into two parts, background and objects, and both populations follow a normal distribution (Arifin and Asano, 2006). Pixels with a less intense grey tone are transformed to white and those of a darker grey than the threshold to black. By this means it is possible to obtain a binary image in which rock fragments were represented by a black pattern and the fine earth as white. An automated threshold was also used and compared to results obtained by manual thresholding.

Quantification of the rock fragment content was attempted by counting the number of black and white pixels from the black and white image.

3.2. The results from image processing explained in 3.1 were compared to a methodology that is being developed at the Public University of Navarra. In this new approach, image processing was carried out by using an experimental logarithm that consists on grouping image features by their similar colour characteristics.

Therefore, three image processing approaches were compared:

- Image Tool 3.0. with manual thresholding.

- Image Tool 3.0. with automatic thresholding.
- Experimental algorithm.

Results from these methodologies were compared to the visual estimation performed by using FAO charts.

4. Results and Discussion: The resulting coverage of rock fragments from the different image analysis techniques are depicted in Table 6 and compared to the visual estimation method.

Table 6. Rock fragment coverage (%) obtained from the image processing by different methodologies compared to visual estimation by FAO charts.

Soil	Visual estimation	Image Tool 3.0 Manual	Image Tool 3.0 Automatic	New algorithm
Cascante 1	0	0.1	6.95	4
Fontellas 1	0	6.17	9.92	8
Funes 1	0	0.6	5.9	7
Funes 2	5	1.0	5.2	5
Cascante 2	0	1.0	1.0	1
Fontellas 2	15	7.6	9.7	7
Fontellas 3	12.5	9.9	9.9	11
Fontellas 4	0	13.2	15.3	12
Fontellas 5	0	8.1	10.8	7
Tafalla 1	45	51.8	39.9	81
Tafalla 2	8	17	28.8	45
Olite	55	32.6	76.4	79
Pitillas	78	32.4	69.1	100
Ausejo 1	30	13.5	6.4	13
Ausejo 2	15	10.8	15.3	19
Chalet	25	6.44	7.5	3
Miraflores	60	4.66	10.5	10

Better results, expressed as the agreement between the visual estimation and the image analyses, were found for images with a rock fragment coverage lower than 20%, except for Fontellas 4 and Tafalla 2, because differences in rock fragments estimated by the image processing approaches and the reference method were lower than

10% which, as mentioned before, could be settled as an acceptable margin for rock fragment variability.

However, images with higher coverage of rock fragments were less accurately predicted. The automatic thresholding showed better estimations for these higher rock fragment coverages, although the use of a manual thresholding was a better option because in some pictures the results of the automatic process associated to the presence of rock fragments did not correspond to them. Therefore, results from the manual thresholding were more accurate than the ones obtained by the automatic thresholding or the new algorithm overall.

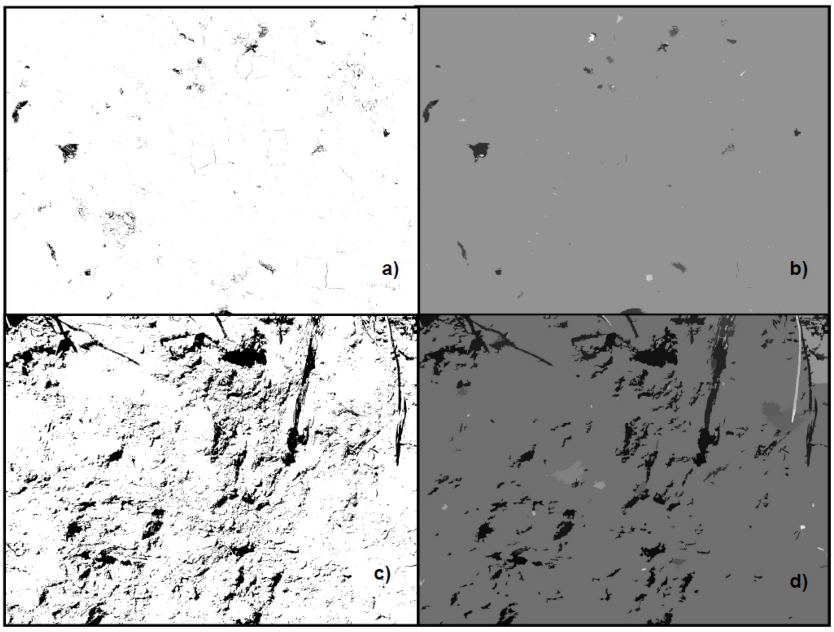

Figure 6. Processed images from a cross soil section area profile: a) Cascante, Image Tool 3.0 manual threshold; b) Cascante, experimental logarithm; c) Fontellas 4, Image Tool 3.0 manual threshold; d) Fontellas 4, experimental logarithm.

It is necessary to point out that during these analyses, several properties of the images taken impeded to achieve a better result. The presence of residues on the soil surface, and also plastic or shadows created by the light, led to incorrect estimations. Some examples of these problems are depicted in Figure 6, in which it is possible to observe images obtained though Image Tool 3.0 and the experimental algorithm. In all four images the rock fragment coverage was overestimated due to the presence of plastic (a, b) or shadows (c and d).

An attempt for estimating soil stoniness by digitized images was made by Andrades et al. (2007). These authors took pictures from the surface stoniness and pictures from the soil profile. They estimated the surface coverage of rock fragments by also using the FAO charts explained before. Similarly, they reported a higher variability in the estimations due to great complexity of the rock fragments distribution (size, type, and distribution though the soil profile).

Therefore, these results indicate that image analysis is a technique more adapted to soils with low proportions of rock fragments. However, at these levels, despite losing an acceptable amount of efficacy in assessing the rock fragment content, the time and labour costs decrease would justify the further research for an automatization.

In any case, it seems clear that for an improved outcome of using image processing techniques, it is necessary to follow certain instructions before taking the pictures:

- Before acquiring the image, it is very important to avoid shadows that could be confused with rock fragments during the processing. Special attention has to be paid to soils with higher coverage of rock fragments in which some fragments can overshadow the others.
- It is better to avoid soils that have been recently ploughed where the presence of soil aggregates of big size is abundant and could also be confused with rock fragments.
- If the soil matrix shows a colour similar to the rock fragments it would be better to take the pictures just after a rain event in order to improve the differentiation process of rock fragments from the background.
- Apart from rock fragments and the soil matrix, no different items like crop or plastic residues should appear on the image.

By following these recommendations, the precision of image analyses may be not as high as using the FAO charts but it will be possible to reduce errors associated to the observer. This would facilitate the assessing of rock fragments coverage in many farms or areas by users with no specific training on soil science like farmers. Besides, this system could be up-scaled to regional studies for general information gathering in which evaluations of tilling aptitude could be assessed.

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Chapter III

Conservation agriculture in irrigated Mediterranean gravelly soils. Influence on crop production and soil properties

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CHAPTER III

Conservation agriculture in irrigated Mediterranean gravelly soils. Influence on crop production and soil properties

ABSTRACT

Conservation Agriculture (CA) or the reduction of N addition, are validated techniques for sustainable agriculture in dryland farming. However, the potential effect of adopting no tillage (NT) and reduced N fertilization rates on crop production and soil properties needs to be re-evaluated when used under irrigation and on soils with severe limitations, such as stoniness. Crop yields, total and particulate organic C, total N, available P and K, and the soil water retention and conservation characteristics were monitored under conventional and NT in a gravelly experimental field converted from dryland to irrigation, and cropped to wheat, maize and sorghum. No differences in yields were observed. Soil organic carbon (SOC) and N significantly increased after 2 years since the experiment started, under NT and CT. Therefore, the use of crops with more productive potential with irrigation favored the storage of increased C inputs from crops as SOC. Under NT, these inputs were more protected or less disturbed resulting in higher fertility values and SOC contents at the 0-5 cm depth specially in sector 2, in only two years. In addition, a greater water-holding capacity at the upper soil layer was found, mainly due to greater water retention at saturation and -33 kPa, Furthermore, crop residues left on the soil under NT reduced evaporation between irrigation and rainfall episodes more than rock fragments alone in CT. NT seems a valid strategy to increase SOC and nutrients storage, while optimizing water-use efficiency in irrigated gravelly soils.

INTRODUCTION

The protection of the environment together with the conservation and optimization of natural resources are increasingly considered by European agricultural policies. From a practical point of view, this is being translated into the spreading of the so-called sustainable production techniques, which optimize inputs and are as much environmental-friendly as possible.

Conservation Agriculture (CA) is seen as an adequate strategy in this sense. CA is associated to conservation tillage, which comprises reduced and non-inversion tilling with at least 30% of crop residues remaining on the soil surface (Hobbs et al., 2008), as well as no tillage (NT) systems with direct seeding. These systems are known to have an effect on soils, especially in relation to soil organic carbon (SOC) storage at the surface layer, the soil water retention capacity and soil fertility. They can also contribute to reduce erosion and nutrients leaching (Hobbs et al., 2008; Pittelkow et al., 2015; Fernández-Romero et al., 2016).

In addition to the plethora of local studies on the effect of CA on SOC and/or soil fertility, survey studies have been also conducted at a global and national level (e.g. Kern and Johnson 1993; West and Post, 2002; VandenBygaart et al. 2003; Lal, 2004; Zinn et al., 2005; González-Sánchez et al., 2012). In general, these studies show a positive effect of CA on soil organic C stocks, which is however site-dependent (e.g. Kopittke et al., 2016), and can vary greatly among regions and soils (Powlson et al., 2014). In the case of NT, its contribution to greater crop yields is a key factor for observing a net SOC gain (Ogle et al., 2012; Virto et al., 2012). Yields response to NT, when compared to conventional tillage, can be in fact variable, depending on climatic conditions, residue management and crop rotation (Pittelkow et al., 2015).

In relation to the soil water retention capacity, many studies have been conducted in drylands reporting an increase of available water for crops with CA because of reduced evaporation and increased water storage capacity of soils (e.g. West and Post; 2002; Bescansa et al., 2006; Moreno et al., 2006; Imaz et al., 2010; Varvel and

Wilhelm, 2011). In rainfed agriculture, this is crucial because it determines the amount of water available for crop production. Besides, conservation tillage may contribute to improve soil structure (Huang et al., 2015) and, therefore, to an optimization of water use.

These and other reasons related to the reduction in cost, have led to the adoption of CA by farmers in many regions worldwide (Hobbs et al., 2008). At present, around 9% of the global arable land is under no-till (Pittelkow et al., 2015). In semi-arid regions, such as many areas of the Mediterranean Basin, where water is the most significant limiting factor for agriculture, it has become an extended practice, basically on drylands. For instance, in the Ebro Basin it accounts for around 20% of the agricultural land, mostly concentrated on drylands (Fernández-Ugalde et al., 2009).

In many of these semi-arid areas, irrigation is spreading under the pressure of increased food demand, and in search of agricultural systems less dependent on natural water limitations, and with a greater potential productivity. This is part of a global trend: according to FAO (2011), irrigation is gaining relevance worldwide in the last decades, and it accounts for around 20% of the total cultivated land (FAO, 2011).

In this context, the adoption of CA and its potential consequences on soil and soil fertility need to be re-evaluated in detail, as farmers can be reluctant to adopt CA in arid and semi-arid areas, when water is no longer a productivity limiting factor, and the ability of NT to maintain greater yields is not clear.

In relation to soil condition, the introduction of irrigation could induce changes in the effectiveness of CA for increasing SOC, in some aspects. First, it increases the net primary productivity of the system, and therefore the potential C inputs to the soil, regardless of the tillage system. Second, it also modifies SOC mineralization rates, as more water is available when temperatures are adequate for microbial degradation of organic matter (Gillabel et al., 2007; Apesteguia et al., 2015). These two aspects can modulate the final response of SOC to NT in irrigated land, both in terms of yield differences with conventional tillage, and in relation to the time required to observe significant changes. For instance, some model results in Mediterranean conditions showed that the shift from rainfed conditions to irrigation would result in an increase of C inputs but a decrease in the SOC sequestered in a time-span of 90 years (Álvaro-Fuentes and Paustian, 2011).

The changes in the soil annual water balance with irrigation can also have consequences in terms of the water-use efficiency of different tillage systems, as well as on nutrients leaching and up-take by plants. In this sense, CA can be still interesting in irrigated systems because of the benefits it has in terms of the regulation of the soil water balance, and for soil protection against degradation (Arroyo Garcia et al., 2012; Fernández-Romero et al., 2016).

Additionally, another significant aspect in irrigated fields compared to rainfed agriculture is nitrate leaching, which stands as an important environmental issue if nitrogen is not managed properly. The more intensive agriculture practiced with irrigation makes the optimization of N inputs especially important. A well-balanced management could be achieved by rationalizing the use of nitrogen following regulated practices like those of Integrated Production (IP) in Spain, in which crop production is controlled by established standards that assure inputs optimization together with the use of more sustainable techniques (Boller et al., 2004). Under this standard, as in many other frameworks proposed for sustainable agriculture, the recommended amount of nitrogen to apply is reduced compared to conventional management. This can lessen the environmental problems associated to excessive fertilization, and also lead the economic balance into a higher profitability, but also have an impact on soil and crop production, which needs to be controlled.

Finally, another aspect that needs to be considered when assessing CA in irrigated agrosystems is that the implementation of irrigation in many semi-arid areas previously devoted to dryland farming is leading to the expansion of intensive agriculture to soils with reduced agricultural aptitude in dryland conditions. This is the case of gravelly and stony soils, where the presence of rock fragments at the soil surface can limit both crop development and soil management by impeding tillage (Soil Survey Division Staff, 1993).

The interaction of CA with this type of soils can be challenging in this context (e.g. Schwilch et al. 2015), and little information is available on the potential consequences of NT implementation on gravelly and stony irrigated soils on crop yields, soil quality and nutrients-use efficiency. Still, information is needed to explore the potential of using CA techniques in irrigated agrosystems on marginal soils, coupled with a more efficient management of nitrogen fertilization.

In this context, the goal of this work was to study the effect of NT adoption in comparison to conventional soil management (CT) in a gravelly soil converted to irrigation, in terms of (i) crop yields, (ii) nutrients availability and its interaction with N optimization, and the soil organic fraction, and (iii) the soil water retention ability and water dynamics.

MATERIALS AND METHODS

Site description. The study site was located in Olite (42º 26´ 50.10´´N; 1º 38´ 28´´W), in NE Spain, within the Ebro river basin. Traditionally this area practiced rainfed agriculture based on vineyards and extensive cereals and irrigation was introduced in 2010. Climate is temperate Mediterranean (TE Me) by the Papadakis classification (1975), with an annual precipitation close to 500 mm. An experimental trial was implemented in a field located on the Cidacos river terrace system, formed by Qaternary alluvial deposits. The soil, gravelly and with a sandy-clay loam texture, was classified as a Petrocalcic Calcixerept (Soil Survey Staff, 2014). It is a shallow soil, with an effective depth of 30-35 cm because of the presence of a pretrocalcic horizon. In accordance with the specific characteristics of these terraces, the soil had a high rock fragment content through the whole profile with rock fragments sizes ranging from 20 to 60 mm.

Soil fragments were quantified in soil samples obtained by excavating a representative elementary volume "REV" (Bear, 1972) at 0-5 cm, 5-15 and 15-30 cm for the different treatments of the experimental field (see below). Large rock fragments were firstly separated by hand and weighted. The remaining material of each sample were air-dried and sieved through a mesh of 2 mm. Sample material > 2 mm was immersed in a sodium hexametafosphate solution in order to disaggregate the fine earth attached to rock fragments, washed and oven-dried at 105 ºC. The gravimetric content of rock fragments was calculated by summing the mass of all rock fragments contained in the sample and reporting it to the total sample mass (Table 1). The volume of the rock fragments was determined by the water displacement of their mass.

Table 1. General soil characteristics and soil rock fragment content (n=6) depending on the tillage system. CT: conventional till; NT: no till.

Horizon	**Ap1**	**Ap2**	**C**
Depth (cm)	**0 - 15**	**15 - 35**	**35 - 60**
Particle size distribution (g Kg^{-1})			
Sand (50 - 2000 µm)	640.8	621.7	807.4
Silt (2 - 50 µm)	135.0	144.6	78.8
Clay (< 2 µm)	220.3	236.2	136.8
Bulk density fine earth (Mg m^{-3})	1.48	1.58	-
CaCO3 (g Kg^{-1})	269.8	252.3	842.2
pH	8.0	8.0	-
Electrical conductivity (µS cm^{-1})	246	264	-
CEC (cmol Kg fine $earth^{-1}$)	13.04	14.85	-
Rock fragment content (g 100 g^{-1})			
		Sector 1	
CT	58.21a ± 1.94	47.87a ± 2.12	48.36a ± 3.52
NT	64.25 a± 2.54	47.91a ± 1.20	49.82a ± 1.53
		Sector 2	
CT	71.34a ± 1.53	51.77a ± 1.67	50.37a ± 2.41
NT	68.27a ± 3.67	53.09a ± 5.01	44.97a ± 2.65
		Sector 3	
CT	52.54a ± 2.62	39.09a ± 1.73	37.07a ± 1.67
NT	50.95a ± 3.23	39.36a ± 2.62	40.84a± 2.68

Soil characteristics can be seen in Table 1. The soil had no salinization problems, the drainage was good and the slope < 2%.

Experimental design. The study was established in a field recently converted to irrigation, with three independent irrigation sectors. Each sector followed a crop sequence that included sorghum (*Sorghum vulgare* L.), winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.). The experiment started in 2011, one year after irrigation started, and this year was considered as the baseline of the study (year 0), which was conducted during two more years (year 1 and year 2).

A randomized split-plot design with three replicates was adjusted to the field's sprinklers distribution (15 x 18 m). Plots had a dimension of 6 x 13 m. Two factors were analysed in this study: the tillage system and nitrogen fertilization. For the tillage system, no till (NT) and conventional tillage (CT) were tested. NT consisted on direct seeding maintaining crop residues at the soil surface. Conventional tillage involved various chisel-ploughing operations to a depth of 15 cm that incorporated crop residues into the soil, followed by seedbed preparation using a cultivator. In addition, two types of N fertilization (urea 46%) were tested: conventional and reduced N fertilization. Plots defined as F1 received the conventional N dose in the area (150 kg/ha for wheat and 300 kg N/ha for maize and sorghum). F2 plots received ~20% less of that dose following the recommendations for a more sustainable crop production (120 kg/ha for wheat and 250 Kg N/ha for maize and sorghum). The different N fertilization rates were applied at tillering stage (wheat) and 6-leaves stage (maize and sorghum), following conventional fertilization routines in the region. Phosphorus was added equally to all plots at a dose of 70 kg/ha prior to sowing.

An attack of *Sesamia nonagrioides* occurred in year 2 affecting maize CT plots.

In year 0, all plots were tilled using CT in order to avoid heterogeneities due to previous management. In year 1, the second year of the experiment, it was necessary to till NT plots from sector 1 with a chisel plow (twice) and a seedbeed preparator to a depth of 3-4 cm in order to control weeds proliferation. During this year, NT plots from sector 2 received a land roller pass while sector 3 plots under this tillage treatment remained undisturbed. In year 2 there was no incident and tillage treatments were applied as defined.

Field and laboratory methods. Plant emergence was determined for every crop. Wheat plants were measured by counting the number of plants emerged per m^2. Sorghum and maize emergence was obtained by counting the number of plants in 2 linear meters. Plots from different treatments were harvested at the same physiological growth stage. Data for yields, specific kernel weight (SW) for maize and wheat grains and the weight of thousand wheat kernels weight (TKW) were recorded. Three subsamples were collected from every plot and dried at 105ºC for moisture correction and determination of the harvest index.

Soil samples were compiled during the three years of the experiment for the different treatments tested. Disturbed samples were collected for the 0-5 cm, 5-15 cm and 15-30 cm of depth. Three randomized soil samples were used to make a composite sample for each treatment, layer, and replication. Sample material was air-dried and sieved to pass a 2 mm mesh and thoroughly homogenized for its analysis. The fraction < 2 mm (fine earth) was used for subsequent analyses.

Soil bulk density was obtained by using the excavation method (Blake and Hartge, 1986). Soil samples were excavated and removed from the soil, a plastic foil was placed on the hole and then filled with water to determine its volume. Bulk density of the fine earth < 2 mm was calculated by subtracting the mass and the volume the rock fragments occupy.

Total soil organic C (SOC) was determined by wet oxidation (Tiessen and Moir, 1993) due to the high carbonate content in the soil (Table 1). The particulate organic matter (POM) was isolated by the method described in Virto et al. (2007) where 10 g of air-dry soil were dispersed and sieved for collecting the organic matter fraction > 53 µm. Organic C in this fraction (C-POM) was measured by wet oxidation after grounding the POM fraction to a powdery consistency. Kjeldahl digestion method was applied to obtain the total N from the samples. Available P was determined following the methodology described by Olsen and Sommers (1980). NH_4OAc 1N was used for extracting the exchangeable K contained in the soil and its quantification was carried out by atomic absorbance (Knudsen et al., 1982). The concentration of soil properties in the soil was obtained by correcting their fine earth concentrations by the content of rock fragments present in the soil (Table 1).

The influence of tillage (NT vs CT, regardless of N dose applied) on water dynamics was studied in sector 3 for being the sector that did not suffer any incidence regarding to tillage treatments.

Soil water retention curves were determined for samples from the 0-5 cm and 5-15 cm depths. Water retention (SWC) at matric potentials of -33 kPa, -50 kPa, -150 kPa and -1500 kPa were measured by using pressure plate extractors (Soil Moisture Equipment Corp., Santa Barbara, CA) as described by Dirksen (1999). Measurement of the water content at saturation was also obtained using the saturated paste methodology proposed by Pansu and Gautheyrou (2006). Volumetric values for SWC were calculated from gravimetric values using the bulk density of the fine earth and the volume occupied by rock fragments in the soil, as expressed in the following equation (equation 1):

$$\theta = w \times BD_{\text{Fine earth}} \times (1\text{-}S) \qquad \text{Equation 1}$$

where θ (m^3 m^{-3}) is the volumetric water content, w (g g^{-1}) is the gravimetric water content, $BD_{\text{Fine earth}}$ (g cm^{-3}) is the bulk density of the fine material (< 2mm), and S (m^3 m^{-3}) is the volumetric content of rock fragments. The volumetric value of rock fragments was calculated from the gravimetric measures using the bulk density of the soil divided by the density of the rock fragments. The resulting data from the water retention were fitted to the van Genuchten (1980) mathematical function using the RETC code of van Genuchten et al. (1991) which is a computer program used to analyse the soil water retention and hydraulic conductivity functions of unsaturated soils. The saturated water content (θ_s), the residual water content (θ_r), and the empirical fitting parameters describing the water retention curve shape (α, n) were obtained.

The available water-holding capacity of the soil (AWHC) was obtained as the difference of soil water content at field capacity (-33 kPa) and wilting point (-1500 kPa). Water contents at the measured pressure heads were also used to estimate the relative frequency of pore size distribution. Based on different models and equations (Rose, 1966; van Genuchten, 1980; Carter and Ball, 1993) equivalent pore diameters were calculated following Bescansa et al. (2006) indications: 9 µm for -33 kPa, 6 µm for -50 kPa µm and 0.2 µm for -1500 kPa. These authors assumed that pores were cylindrical capillaries as described in the Laplace-Young equation (Leij et al., 2002).

Finally, the drying dynamics of the soil was studied *in situ*, in order to evaluate the effect of NT on evaporation. During year 2 of the experiment, a soil section (0.2 m^2), free of plants, from CT and NT plots was covered by a plastic foil with the purpose of avoiding evaporation. Soil was sampled in these sections and contiguous non-covered sections 24, 48, 120, 192, 360 and 480 hours after an irrigation event. Samples were taken from the covered and no-covered areas at a depth of 0-15 cm. Three replicates were performed for every tillage treatment.

Statistical analysis. Data were analysed using the univariate linear model (ANOVA) for determining significant differences among treatments. Homogeneity of variances was verified by the Levene test. Post-hoc analysis was carried out by the Duncan's test. Significant differences were based on a probability level of $p < 0.05$ unless otherwise indicated. These statistical analyses were performed using the SPSS 18.0 software (SPSS Inc., 2009).

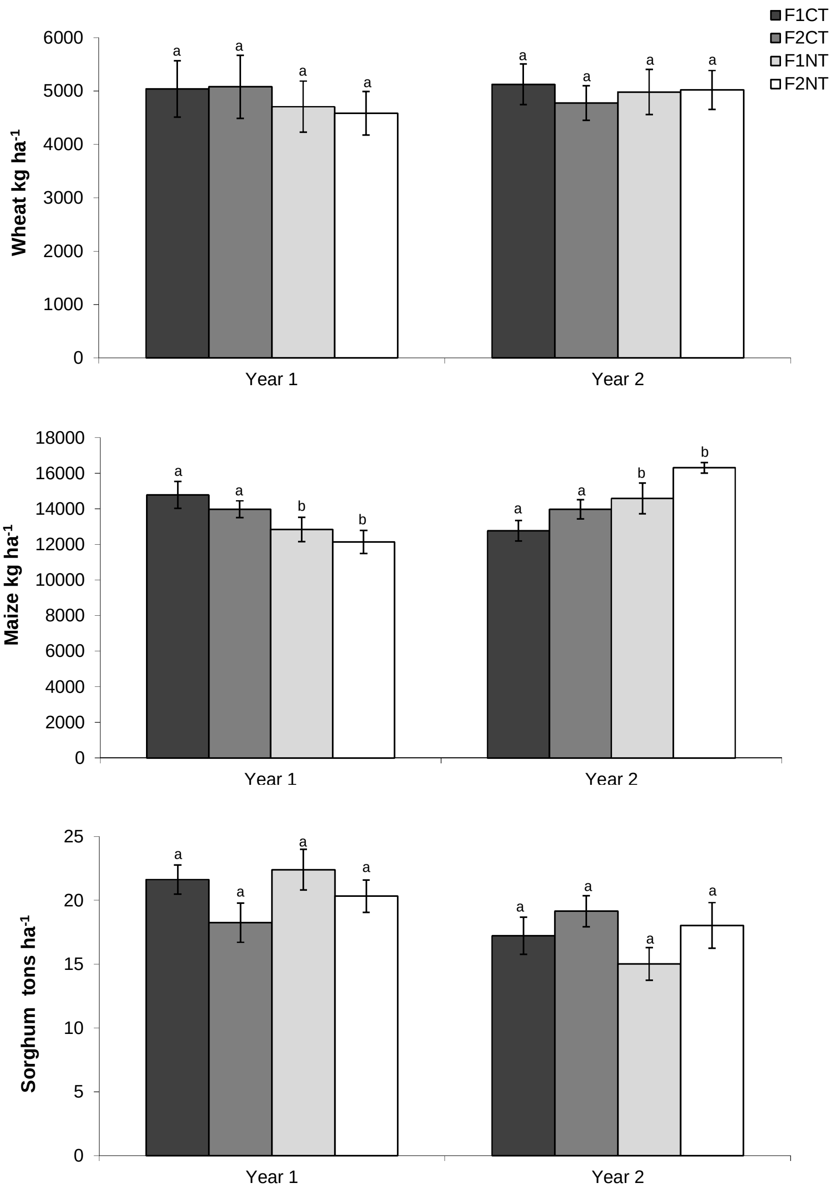

Figure 1. Yield obtained by the different crops during year 1 and year 2 according to the treatments studied (n=3). F1: conventional nitrogen fertilization rate; F2: reduced nitrogen fertilization rate; CT: conventional till; NT: no till. Different letters indicate significant differences between treatments ($p < 0.05$) for the same year.

Table 2. The effect of tillage and N fertilization rates on crops emergence and yield parameters during year 1 and year 2 (n=3). SW: specific kernel weight; TKW: weight of thousand wheat kernels. F1: conventional nitrogen fertilization rate; F2: reduced nitrogen fertilization rate; CT: conventional till; NT: no till.

	F1 CT	F2 CT	F1 NT	F2 NT
		Wheat year 1		
Emergence (plants m^{-2})	536.67a ± 24.52	515.83a ± 39.80	518.33a ± 4.41	684.17b ± 63.95
Moisture content (%)	11.93a ± 0.12	11.57b ± 0.09	11.83a ± 0.13	11.63b ± 0.12
SW (kg hl^{-1})	78.17a ± 0.80	78.37a ±0.73	78.53a ± 0.74	78.00a ± 0.91
TKW (g)	29.52a ± 1.15	29.57a ± 0.57	29.46a ± 0.65	28.91a ± 0.37
Yield index (%)	46.33a ± 1.33	44.33a ± 2.73	47.00a ± 1.53	45.33a ± 2.03
		Wheat year 2		
Emergence plants m^{-2})	248.00a ± 6.43	207.33a ± 12.02	135.33b ± 23.13	127.33b ± 14.11
Moisture content (%)	10.70a ± 0.31	11.10a ±0.10	10.83a ± 0.03	10.90a ± 0.06
SW (kg hl^{-1})	74.57a ± 1.38	76.17a ± 0.41	75.87a ± 0.37	75.80a ± 0.15
TGW (g)	34.51a ± 1.42	34.96a ± 0.35	36.38a ± 0.98	35.05a ± 1.18
Yield index (%)	49.24a ± 3.06	52.44a ± 2.46	52.26a ± 0.14	51.99a ± 2.32
		Maize year 1		
Emergence (%)	96.67a ± 3.33	96.67a ± 3.33	90.00b ± 0.00	90.00b ± 0.00
Moisture content (%)	22.90a ± 0.29	22.67a ± 0.20	22.27a ± 0.32	22.83a ± 0.47
SW (kg hl^{-1})	67.27a ± 0.73	67.77a ± 0.77	67.30a ± 0.62	67.50a ± 0.25
Yield index (%)	57.03a ± 4.26	62.17a ± 1.45	57.43a ± 2.65	61.34a ± 1.20
		Maize year 2		
Emergence (%)	100.00a ± 0.00	100.00a ± 0.00	77.78b ± 5.56	85.19b ± 9.80
Moisture content (%)	20.83a ± 0.38	20.87a ± 0.50	20.33a ± 0.22	20.57a ± 0.13
SW (kg hl^{-1})	67.40a ± 0.30	68.80a ± 0.76	68.87a ± 0.52	69.43a ± 0.52
Yield index (%)	50.47a ± 2.99	58.29a ± 0.83	62.59b ± 0.78	61.19b ± 2.45
		Sorghum year 1		
Emergence (plants m^{-2})	59.00a ± 5.86	49.00b ± 2.00	29.67c ± 8.82	14.33d ± 2.96
Moisture content (%)	73.57a ± 0.99	73.90a ± 1.41	74.15a ± 0.26	75.10a ± 0.78
		Sorghum year 2		
Emergence (plants m^{-2})	58.00a ± 2.94	42.22a ± 2.22	30.00b ± 1.92	30.00b ± 5.09
Moisture content (%)	77.20a ± 1.20	75.90a ± 0.73	77.46a ± 0.92	77.92a ± 0.99

Different letters indicate significant differences ($p < 0.05$) between treatments in the same row.

RESULTS

Crop production and yield parameters. There were no differences in plant emergence or crop yields for any crop in year 0 (data not shown), when all plots were managed with CT. However, in year 1 and 2 emergences were lower under NT for the different crops (Table 2), except for maize under NT and F2 in year 1. Besides, there was an interaction between tillage and N fertilization rate for sorghum, which induced a lower emergence under NT and also under F2 in year 1.

Despite the differences observed in plant emergence, wheat and sorghum yields did not show any difference between treatments in any of the three years of the experiment. However, maize production was different depending on the tillage system used (Figure 1).

In year 1, yield was higher under CT while in year 2 it was higher under NT. The latter coincided with a higher yield index (ratio grain/residue) for NT plots (Table 2), which meant a higher production of grain per plant.

Wheat F2 plots showed a higher grain moisture content in year 0. However, this pattern was reversed in year 1 with a higher moisture content for F1. Also, maize grain moisture in year 0 was lower for F2 plots together with a higher SW (Table 2). Apart from this, yield parameters were similar between treatments for the studied crops.

Evolution and influence of treatments on soil fertility. The study of soil fertility focused on two factors: The availability of N, P and K for plants, and the content in SOC and C-POM, as indicators of the soil organic fraction. No interactions between tillage and fertilization rates were observed in any of the studied years except for C-POM and C:N in year 2, and in accordance with the small observed differences in yields (see section crop production and yield parameters), no significant differences were observed either for any of these parameters between fertilization doses. These results are therefore shown as the average for all N doses for each tillage treatment. The evolution and impact of tillage on SOC and C-POM in sector 3 is more thoroughly analysed in Chapter IV “Implications of rock fragments for soil organic C and soil quality evaluation: Assessing changes in a gravelly irrigated soil following no till adoption".

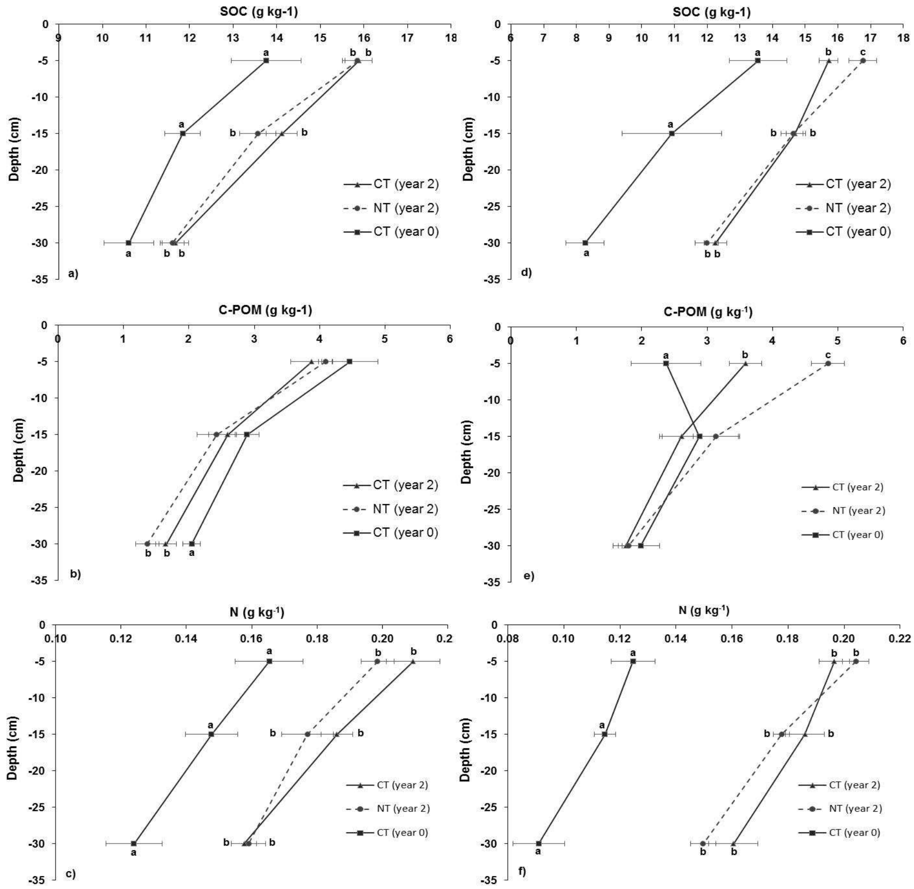

Figure 2. Evolution of SOC, C-POM and N values for the fine earth from year 0 to year 2 depending on the tillage treatment (n=3 for year 0 and n=6 for year 2), in sector 1 (a, b, c) and 2 (d, e, f). CT: conventional till; NT: no till.

The effect of tillage (CT vs. NT) induced differences in soil fertility in two senses. First, an evolution was observed from year 0 to year 2. A significant increment in this time lapse was observed for N and SOC contents both for NT and CT (Figure 2).

Table 3: P and K obtained at year 0 and year 2 of the experiment for the different tillage treatments (n=6). CT: conventional till; NT: no till.

		P Olsen (mg Kg^{-1})	Available K (mg Kg^{-1})
		Sector 1	
0-5 cm	CT	31.22a ± 3.17	213.68b ± 27.05
	NT	54.60b ± 9.68	253.02b ± 22.12
	Year 0	31.80a ± 1.97	382.52a ± 44.43
5-15 cm	CT	15.69a ± 2.88	166.09b ± 14.99
	NT	10.36b ± 1.19	145.34b ± 9.20
	Year 0	22.10a ± 2.77	233.48a ± 19.69
15-30 cm	CT	7.82b ± 0.94	122.19b ± 12.29
	NT	5.90b ± 0.53	118.15b ± 6.50
	Year 0	16.23a ± 1.17	179.00a ± 9.80
		Sector 2	
0-5 cm	CT	28.06a ± 4.21	171.88a ± 11.88
	NT	40.00a ± 5.38	232.58a ± 35.21
	Year 0	42.60a ± 2.40	183.34a ± 0.85
5-15 cm	CT	14.92a ± 2.17	135.01b ± 9.99
	NT	13.59a ± 1.59	172.93ab ± 25.40
	Year 0	18.19a ± 1.82	228.77a ± 48.85
15-30 cm	CT	5.96b ± 0.82	109.32b ± 2.85
	NT	6.84b ± 0.81	122.75b ± 8.05
	Year 0	13.11a ± 2.73	262.90a ± 17.03
		Sector 3	
0-5 cm	CT	34.02a ± 5.93	301.27a ± 48.37
	NT	40.86a ± 8.75	600.65b ± 140.79
	Year 0	24.75a ± 3.02	206.27a ± 21.10
5-15 cm	CT	17.89a ± 2.19	222.03a ± 29.24
	NT	15.81a ± 1.70	296.20a ± 84.37
	Year 0	18.16a ± 2.67	213.13a ± 13.00
15-30 cm	CT	19.03a ± 2.50	197.41a ± 19.59
	NT	14.69a ± 2.50	198.14a ± 19.91
	Year 0	13.30a ± 1.52	249.11a ± 69.89

Different letters indicate significant differences ($p < 0.05$) between treatments in the same depth

C-POM was also higher for year 2 under NT at 0-5 cm but only for sector 2. K and P contents are displayed in Table 3. K contents were higher for year 0 in sector 1 at all depths studied whilst sector 2 contents were only higher at the 15-30 cm.

Table 4: N, P, K, C:N, SOC (g kg^{-1}), C-POM (g kg^{-1}) and C-POM:SOC of the fine earth for the different tillage treatments during year 2 after rock fragment correction (n=6). CT: conventional till; NT: no till.

	0 - 5 cm		5 - 15 cm		15 - 30 cm	
	CT	NT	CT	NT	CT	NT
Sector 1						
N (g kg^{-1})	0.13a ± 0.01	0.13a ± 0.00	0.12a ± 0.00	0.11a ± 0.01	0.10a ± 0.00	0.10a ± 0.01
P Olsen (mg kg^{-1})	20.06a ± 2.04	35.08b ± 6.22	10.08a ± 1.85	6.66a ± 0.77	5.03a ± 0.61	3.79a ± 0.34
Available K (mg kg^{-1})	137.29a ± 17.38	162.56a ± 14.21	106.71a ± 9.63	93.38a ± 5.91	78.50a ± 7.89	75.91a ± 4.18
SOC (g kg^{-1})	10.20a ± 0.20	10.18a ± 0.22	9.07a ± 0.23	8.72a ± 0.27	7.50a ± 0.20	7.45a ± 0.17
C-POM (g kg^{-1})	2.49a ± 0.21	2.63a ± 0.07	1.67a ± 0.19	1.56a ± 0.19	1.06a ± 0.10	0.87a ± 0.11
Sector 2						
N (g kg^{-1})	0.13a ± 0.00	0.13a ± 0.00	0.12a ±0.00	0.11a ± 0.00	0.10a ± 0.01	0.10a ± 0.00
P Olsen (mg kg^{-1})	18.03a ± 2.71	25.70a ± 3.46	9.58a ± 1.39	8.73a ± 1.02	3.83a ± 0.53	4.39a ± 0.52
Available K (mg kg^{-1})	110.43a ± 7.63	149.43a ± 22.62	86.74a ± 6.42	111.10a ± 16.32	70.24a ± 1.83	78.87a ± 5.17
SOC (g kg^{-1})	10.10a ± 0.18	10.77b ± 0.27	9.43a ± 0.17	9.40a ± 0.24	7.87a ± 0.22	7.71a ± 0.23
C-POM (g kg^{-1})	2.30a ± 0.16	3.12b ± 0.16	1.67 ± 0.19	2.01a ± 0.22	1.13a ± 0.12	1.15a ± 0.10
Sector 3						
P Olsen (mg kg^{-1})	17.33a ± 3.02	20.82a ± 4.46	9.12a ± 1.11	8.06a ± 0.87	9.70a ± 1.28	7.49a ± 1.27
Available K (mg kg^{-1})	153.50a ± 24.64	306.03b ± 71.73	113.12a ± 14.90	150.91a ± 42.99	100.58a ± 9.98	100.95a ± 10.15

Different letters indicate significant differences ($p < 0.05$) between treatments in the same depth

However, in sector 3, higher K contents were observed in year 2 under NT for the 0-5 cm depth. Significant differences for P were only found in sector 1 with higher values for year 2 under NT at the upper soil layer.

Secondly, differences were also observed between CT and NT at the 0-5 cm depth. Sector 2 showed higher contents of SOC and C-POM under NT compared to CT. However higher values under NT were only found in sector 1 for P content and also in sector 3 for K.

Finally, the correction of rock fragments (which obviously resulted in smaller values in all parameters and depths), did not change the differences explained above for the fine earth in terms of the effect of tillage and time on soil properties (Table 4). However, it affected the distribution of these properties with depth, because of the heterogeneous distribution of rock fragments with depth (Table 1).

Table 5: Soil water retention characteristics of the soil depending on tillage and depth (n=6). CT: conventional till; NT: no till.

	0-5 cm		5-15 cm	
	NT	CT	NT	CT
	Volumetric water content (m^3 m^{-3}) year 1			
Saturation	0.38a ± 0.01	0.36a ± 0.00	0.43a ± 0.01	0.44a ± 0.01
-33 kPa	0.19a ± 0.00	0.17a ± 0.00	0.21a ± 0.00	0.20a ± 0.01
-50 kPa	0.17a ± 0.00	0.16a ± 0.00	0.19a ± 0.00	0.18a ± 0.01
-150 kPa	0.13a ± 0.00	0.12a ± 0.00	0.14a ± 0.00	0.14a ± 0.00
-1500 kPa	0.09a ± 0.00	0.09a ± 0.00	0.11a ± 0.00	0.11a ± 0.00
	Volumetric water content (m^3 m^{-3}) year 2			
Saturation	0.40a ± 0.00	0.37b ± 0.01	0.44a ± 0.01	0.43a ± 0.01
-33 kPa	0.20a ± 0.01	0.17b ± 0.00	0.21a ± 0.01	0.21a ± 0.00
-50 kPa	0.16a ± 0.01	0.16a ± 0.01	0.17a ± 0.01	0.19a ± 0.01
-150 kPa	0.12a ± 0.00	0.12a ± 0.00	0.14a ± 0.00	0.13a ± 0.01
-1500 kPa	0.09a ± 0.00	0.09a ± 0.00	0.11a ± 0.00	0.11a ± 0.00

Different letters indicate significant differences ($p < 0.05$) between treatments in the same depth

Influence of tillage on soil water retention. The results of the soil water retention curves from the first year after the adoption of soil conservation practices (year 1) did not show significant differences between tillage treatments for the depths studied at any matric potential (Table 5). However, NT at year 2 showed a higher volumetric water content at the 0-5 cm of depth for matric potentials measured at saturation and at -33 kPa (Table 5). This value significantly increased from year 1 to year 2 ($p < 0.10$).

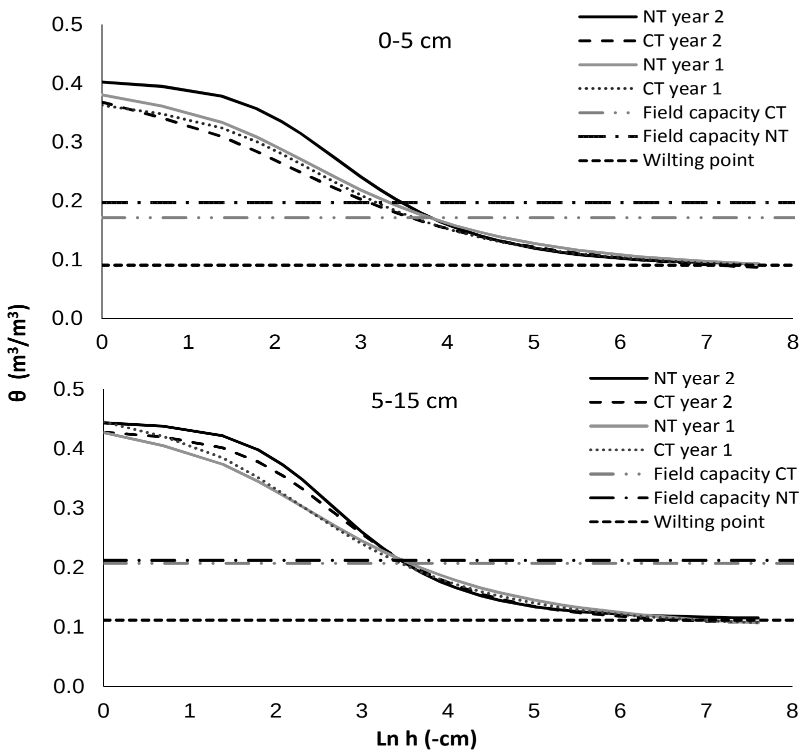

Figure 3. Soil water retention curves from year 1 and year 2 depending on tillage and depth studied (n=6) fitted by RETC. CT: conventional till; NT: no till.

The observed higher SWC at the 5-15 cm depth were the consequence of the higher rock fragment content at the soil surface (Table 1).

Table 6: Soil water retention parameters fitted using the RETC code depending on tillage and depth (n=6). CT: conventional till; NT: no till.

		θr	θs	α	n	R^2	RMSE
0-5 cm	**NT**	0.08 ± 0.01	0.38 ± 0.01	0.18 ± 0.08	1.58 ± 0.16	0.979	0.016
	CT	0.08 ± 0.01	0.36 ± 0.00	0.16 ± 0.05	1.65 ± 0.13	0.973	0.016
5-15 cm	**NT**	0.10 ± 0.01	0.43 ± 0.01	0.19 ± 0.08	1.58 ± 0.16	0.988	0.011
	CT	0.10 ± 0.01	0.45 ± 0.01	0.19 ± 0.10	1.64 ± 0.19	0.972	0.019
0-5 cm	**NT**	0.09 ± 0.01	0.40 ± 0.01	0.10 ± 0.04	1.86 ± 0.26	0.988	0.011
	CT	0.07 ± 0.02	0.37 ± 0.01	0.24 ± 0.20	1.51 ± 0.24	0.993	0.008
5-15 cm	**NT**	0.11 ± 0.01	0.44 ± 0.01	0.10 ± 0.04	2.04 ± 0.36	0.989	0.012
	CT	0.11 ± 0.01	0.43 ± 0.01	0.11 ± 0.05	1.86 ± 0.31	0.988	0.013

The result of fitting the water retention data to van Genuchten (1980) mathematical function using the RETC code are displayed in Table 6. Better water retention curve estimations were achieved for year 2 with higher R^2 and lower RMSE values (from 0.008 to 0.013) compared to year 1. θs was higher for the 5-15 cm depth because of the higher rock fragment content at the soil surface, as commented before. Figure 3 shows the fitted water retention curves at both depths separately. In this figure, it is possible to see that the water content at higher pressure heads (less negative) was greater for NT at year 2, especially at 0-5 cm.

No differences in AWHC were found between tillage systems in year 1. However, AWHC under NT was higher than CT in year 2 (Table 7) for the upper soil depth (0-5 cm). These differences were mainly attributed to water retention at saturation and -33 kPa.

Table 7: Total soil pore volume > 0.2 µm (m^3 m^{-3}), relative pore-size frequency and available water content (AWC) depending on tillage and depth (n=6).

	0-5 cm		5-15 cm	
	NT	CT	NT	CT
Year 1				
AWC (mm)	4.51a ± 0.17	4.17a ± 0.17	9.95a ± 0.45	9.28a ± 0.52
Total pores (> 0.2 µm)	0.286a ± 0.009	0.270a ± 0.004	0.317a ± 0.011	0.335a ± 0.009
Equivalent pore Ø	Relative frequency (%)			
> 9 µm	68.32a ± 1.64	69.15a ± 1.29	68.25a ± 2.32	72.30a ± 1.44
6 - 9 µm	5.65a ± 0.53	6.24a ± 0.51	6.27a ± 0.80	5.47a ± 0.59
0.2 - 6 µm	26.03a ± 1.62	24.61a ± 1.53	25.48a ± 1.94	22.23a ± 1.64
Year 2				
AWC (mm)	5.24a ± 0.43	4.09b ± 0.20	9.96a ± 0.38	9.61a ±0.26
Total pores (> 0.2 µm)	0.313a ± 0.003	0.286b ± 0.011	0.331a ± 0.012	0.319a ± 0.010
Equivalent pore Ø	Relative frequency (%)			
> 9 µm	65.67a ± 2.31	68.70a ± 1.28	69.76a ± 0.76	69.15a ± 1.06
6 - 9 µm	12.46a ± 2.55	5.99a ± 3.80	13.13a ± 3.38	6.83a ± 3.90
0.2 - 6 µm	21.87a ± 3.42	25.31a ± 2.78	17.12a ± 3.58	24.02a ±3.87

Different letters indicate significant differences ($p < 0.05$) between treatments in the same depth

Data from the water retention characteristics were used to estimate the pore size-distribution in the soil. Larger pores (> 9 µm) were more abundant, accounting for more than 60% of the total porosity (Table 7). As a consequence of the larger volume of rock fragments in the upper part of the soil, porosity was lower at the 0-5 cm depth compared to the 5-15 cm one. The tillage system significantly increased the total porosity for the 0-5 cm depth in plots under NT. Pores with a size of 6-9 µm were more than doubled under NT for both depths ($p < 0.10$ for 5-15 cm depth).

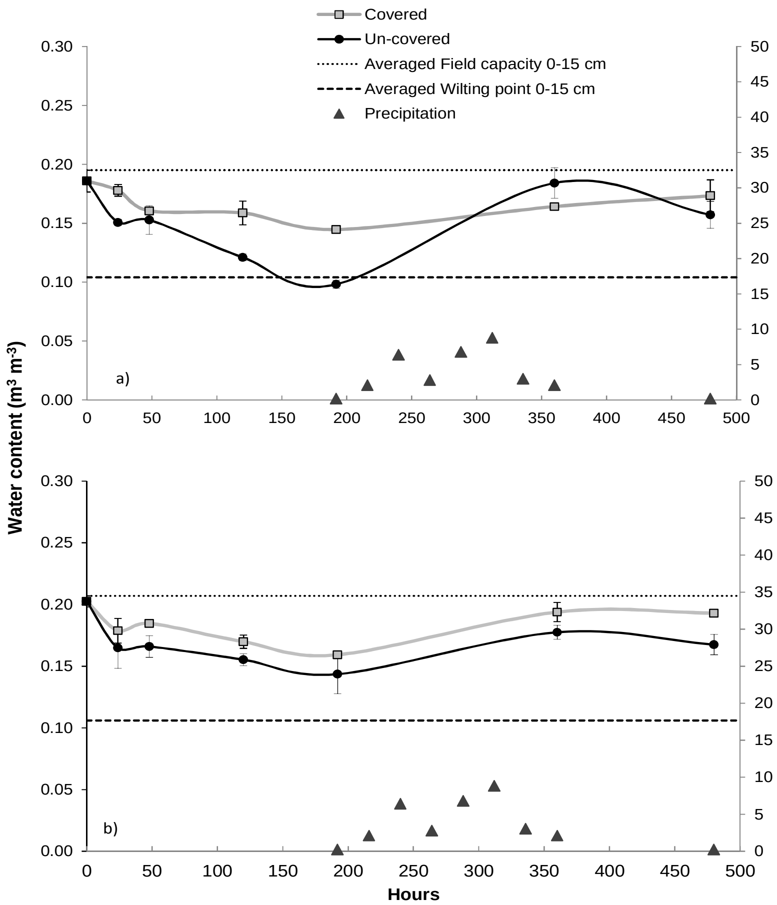

Figure 4. *In situ* drying dynamics in the a) CT: conventional till plots and b) NT: no till plots; (n=3).

The soil water drying curves for both tillage treatments (NT and CT) comparing covered and uncovered soil samples are presented in Figure 4. Different drying patterns were observed between NT and CT when comparing the covered and uncovered areas. CT plots dried more and faster than NT in uncovered areas. CT uncovered samples reached the wilting point 192 h after irrigation, while NT samples were at 65% of the field capacity at that point. No differences were observed in the soil water content between covered and uncovered NT samples during the experiment and their values were closer to field capacity than samples under CT during the whole experiment duration.

DISCUSSION

Crop production. There was an influence of tillage on crop production. Generally, plants found more difficulties for emerging under NT, which can be related to the lower soil temperature under this system (Fabrizzi et al., 2005) but also to the field gravel content (Table 1). In this type of soils, the use of direct-seeding machines with discs, like the one used in our study, is complicated and usually results in the deposition of seeds at very heterogeneous depths (Pérez de Ciriza, 2004). In addition, crop residues left on the surface can difficult the contact between seeds and soil. This effect was also observed by Khaledian et al. (2012) for wheat, maize and sorghum under direct seeding into a crop mulch in comparison with CT. The presence of rock fragments is likely to enhance this effect, contributing to a more irregular emergence in NT than CT.

These differences were however not translated into differences in yield or grain quality (SW or TKW). In the case of wheat and sorghum, where yields were similar between NT and CT, the ability of these crops for developing more spikes during the tillering stage has already been reported to compensate for poor crop establishment (Brennan et al., 2014). In the case of maize, a higher variability in yields was observed between seasons (year 1 and year 2). The lower emergence rates observed in year 2 under NT compared to CT were compensated by a higher yield index, as previously reported in other studies (e.g. Verhulst et al., 2011).

Overall, these results indicate that NT did not result in a clear improvement of crop productivity compared to CT in the studied irrigated gravelly soil, but neither in a loss of it. Besides, grain quality was not affected by the use of conservation tillage. This result is in consonance with other studies conducted with irrigation in Mediterranean and other semi-arid areas (Khaledian et al., 2012; Follett et al., 2013; Khaledian et al., 2014), which did not report significant and consistent differences in crop production depending on tillage. NT has been however reported to produce lower yields in the short-term (Pittelkow et al., 2015; Salem et al., 2015). However, these authors also reported that combining conservative tillage with crop rotation and residue accumulation at the soil surface minimizes the yield reduction, which could explain the results observed in this study.

In relation to other studies developed in non-irrigated conditions, where higher yields under NT have been reported (Lindwall et al., 1995; Melaj et al., 2003; Plaza-Bonilla et al., 2014), our study indicates that the suppression of water scarcity with irrigation also limits the ability of NT to increase yields. This is in agreement with previous studies in the region (Cantero-Martinez et al., 2007), which observed higher yields under conservation tillage in drylands, but not in humid areas.

Finally, there was no interaction between tillage and N rates in crop production, as previously observed by Cantero-Martinez et al. (2003) under Mediterranean semiarid conditions. A rationalized nitrogen fertilization dose did therefore not decrease crop productivity, even under conservation tillage, and could be used to reduce nitrate leaching and decrease farmer’s production costs. This result is in opposition to recommendations proposed by McConkey et al. (2002), who reported that medium and fine-textured soils under rainfed conditions need a higher amount of N fertilization if conservation tillage is used.

Soil fertility and organic matter. Soil macronutrients (N, P and K), as well as the organic fraction were studied to analyse the potential effect of NT adoption and reduced fertilization on soil fertility indicators in irrigated gravelly soils such as the one of this study. No effect of N dose was observed in any of these parameters, which supports the lack of differences in yields described above. The reduction of N fertilization at the rates used in this experiment seem thus to have no consequences in yields, and seem therefore viable in irrigated agroecosystems as the one described here.

However, results showed differences in two senses: the evolution of soil fertility and SOC with time, and an interaction of tillage with this evolution. First, greater SOC and N contents were found three years after the experiment started (year 2) at all studied depths regardless of the tillage system and sector. This can be attributed to the fact that the experimental field had been converted to irrigation from rainfed cereal cropping one year before the onset of the experiment. The role of irrigation in increasing SOC stocks depends mostly on the net balance between increased C inputs from greater biomass production in comparison to dryland cultivation, and increased mineralization rates because of greater water and nutrients availability as reported by Apesteguia et al. (2015). These authors conducted a study comparing SOC stocks and dynamics in irrigated and non-irrigated conditions for maize and wheat in a more humid area and reported an acceleration of SOC turnover rates, but no net gains in SOC after two years of irrigation. The difference with our results, supports the observation of Trost et al. (2013) who reported that the potential of irrigation for increasing SOC is greatly site-dependent.

Secondly, a significant effect of tillage (NT vs. CT) on the studied soil properties, was observed at 0-5 cm, where SOC, C-POM, P and K were higher under NT than CT at year 2 depending on the sector studied but regardless of the correction for stones being applied or not (Figure 2 and Table 3). Year 2 resulted in significantly higher P contents only in sector 1 and K contents in sector 3 for the NT system at the 0-5 cm depth. However, it was possible to observe a tendency to higher values of P and K under conservation practices at this layer in all the three sectors compared to CT. In addition, they were stratified with depth. Similar results were reported by Papini et al. (2007), Deubel et al. (2011) and Neugschwandtner et al. (2014). This enrichment of P and K in the uppermost soil layer under conservation practices compared to CT could be due to the higher residue accumulation that takes place under NT.

On the other hand, the use of conservation practices produced a higher increase of C-POM and SOC in sector 2 but only at the 0-5 cm depth compared to CT. Usually, studies that have reported increments in organic matter contents under NT were also referred to the upper soil layer (Christopher et al., 2009; Dikgwatlhe et al., 2014; Huang et al., 2015). However, this effect was not observed in sector 1. The studies that report increments in SOC under NT associate this observation to a lack of crop residues disturbance by organisms and/or a better protection by soil aggregates. Therefore, this result in sector 1 could be due to tillage operations carried out during year 1 under NT (explained in material and methods).

C-POM was the quickest parameter reacting to changes in soil tillage because is a precocious soil quality indicator sensitive to management changes as described by (Imaz et al., 2010). It was already possible to appreciate in both experimental irrigation sectors a higher content of labile organic matter compared to CT, but not significant in sector 1. However, the higher mean content of C-POM under NT it is expected to be significant with one more year of NT. Other studies also found higher C-POM contents under NT (Aziz et al., 2013; Dimassi et al., 2014). The difference with our research is that those studies were conducted during longer periods of time.

It is important to remark the fact that most changes occurred in the upper soil layer. This supports the role of crop residues at the origin of C, P and K accumulation, as observed previously under NT (Dikgwatlhe et al., 2014; Dimassi et al., 2014; Huang et al., 2015). Similar results of an enrichment in nutrients in the uppermost soil layer under conservation practices compared to CT, with equal fertilization intensities, were also reported by Papini et al. (2007) and Neugschwandtner et al. (2014).

Finally, and in relation to the effect of rock fragments, their role as responsible for the observed behaviour of soil properties cannot be concluded from our data, because no control without rock fragments was available. However, in relation to the research question addressed here, they did not impede the effect of NT adoption, other than regulating the final concentration of soil nutrients and SOC, which can be of importance for the final estimation of organic C stocks and the calculation of fertilization needs. They also affected the vertical distribution of SOC and nutrients (Table 4), which might be of importance if soil quality indexes based on stratification are to be used (e.g. Uclés et al., 2016). This question falls beyond the scope of this work, but merits further research.

Soil physical properties. In relation to the soil physical condition, the goal of this work was to test the efficiency of NT in positively affecting the soil water balance in irrigated conditions on a gravelly soil such as the one in the experimental plot. The effect of NT in the soil water balance has been attributed to both reduced evaporation and increased water storage capacity. The latter has been shown to correspond to the development of a different networks of pores, increasing the ability of the soil to store water at higher (less negative) matric potentials (Bescansa et al., 2006). Our results showed that, after only 2 years of practicing NT it was possible to notice a greater water-holding capacity at the upper soil layer compared to CT (Table 5). This increment was observed at higher matric potentials (less negative), where pores of bigger size are responsible for water dynamics and storage in the soil (Loll and Moldrup, 2000). As shown in Figure 3, the gradual increase of matric potential emptied pores more slowly under NT than CT. This could be due to NT possessing a higher number of pores or having a different pore size distribution (Loll and Moldrup, 2000). However, differences between treatments were not sustained at higher matric potentials because at those levels, water retention is mainly due to adsorption and, therefore, soil water retention is more influenced by soil texture and the specific surface of soil particles than by soil structure (Loll and Moldrup, 2000, Dexter, 2004).

In this sense, rock fragments seemed to have more an effect in the total amount of water available in the soil, than in the capacity of NT to store more water. This was well observed when comparing data of the

0-5 cm and 5-15 cm depths in both CT and NT (Table 5). The greater concentration of rock fragments at the soil surface (0-5 cm, Table 1), made the 5-15 cm depth able to retain more water, especially at higher matric potentials.

The hypothesis of a higher number of pores was confirmed by the estimated values of the water content at saturation which were higher for NT. This result is in agreement with Papini et al. (2007) and Alvarez and Steinbach (2009) that reported a superior water content under NT. In addition, total porosity was significantly enhanced under NT compared to CT. Pores larger than 9 µm were more abundant in this soil accounting for more than 60% of the total porosity. However, the NT system significantly increased porosity at the 0-5 cm depth by enhancing pores of 6-9 µm. This happened in a very short period of time (2 years) in comparison to previous studies in the area in dryland conditions (Bescansa et al., 2006), where changes in the pore size-distribution were observed after 5 years. The increased productivity and available water present in the soil with irrigation, which would allow for a more active microbial activity and organic matter processing (Apesteguia et al., 2015), and thus to a better development of soil structure (Golchin et al., 1994; Angers et al., 1997; Six et al., 2004), were very likely related to this change.

In relation to the consequences of NT in controlling evaporation, the results of the drying experiment (Figure 4) showed that the capacity of NT to reduce evaporation observed in other soil types (Fabrizzi et al., 2005; Alvarez and Steinbach, 2009; Fernández-Ugalde et al., 2009; Verhulst et al., 2011; Salem et al., 2015) remained valid also in the studied gravelly soil. Considering the high percentage of rock fragments present at the surface (Table 1), it could have been hypothesized that evaporation dynamics would be slow and similar in CT and NT, because rock fragments can be a major limiting factor for evaporation (Zhang et al., 2011; Uclés et al., 2016). However, in CT plots, only covered samples showed a similar behaviour than NT plots. For the uncovered plots, only those under NT showed an evolution of soil moisture equivalent to the covered ones. Crop residues left on the soil, and their enmeshment with rock fragments had thus a similar effect on evaporation than the plastic film used in the covered samples.

In relation to water-use efficiency, two facts observed in the drying experiment indicated the differences between CT and NT. First, while a rapid drying to values close to the wilting point was observed under CT in actual field conditions (uncovered) after an irrigation episode that left the field at field capacity (Figure 4), water loss was 35-40% smaller in NT in the same conditions. Second, after a series of rain episodes, CT uncovered samples recovered faster water contents close to field capacity, but it also showed a more rapid decrease than NT uncovered samples (Figure 4). These results support the interest of NT in irrigated soils, where, although water availability is not a limiting factor for crops production, water-use efficiency can be determinant in granting crops profitability and sustainability. Recent studies in Spain (Uclés et al., 2016) have demonstrated that the water productivity (mass of yield per volume of water added) in sprinkler-irrigated rice fields increases greatly when NT is adopted. This observation is also consistent with the described hypothesis of the existence of a pore size-distribution granting a better connectivity under NT. Besides, even under irrigation conditions, a higher holding water content capacity combined with a reduction of evaporation could be critical during the flowering stage when watering is spaced in order to prevent diseases or during hot summers when crops have higher water demands. This, together with the optimization of nitrogen, may avoid nitrate leaching.

CONCLUSIONS

The objective of this work was to gain knowledge of the potential of NT adoption in combination with reduced N fertilization in irrigated land on gravelly or stony soils, in terms of productivity and soil condition.

Although some effects of NT were observed in terms of plant emergence for some crops, our results indicate that NT can be successful in maintaining or improving soil fertility, and in improving the water-use efficiency of the agrosystem in comparison to conventional tillage, while keeping the overall productivity of the system.

Despite of the presence of rock fragments, an increase in the water-holding capacity of the soil was observed with NT at matric potential levels where water movement is driven by capillary forces and, therefore, sensitive to soil management changes. NT also contributed to decrease evaporation rates.

These results, which were observed in only 2 years, in combination with the absence of effects of the reduction in N doses on crop yields or soil properties, indicate that the benefits induced by NT on soil properties could contribute to a more efficient management of irrigated crops.

In addition, the absence of effects of reduced N dose on crop yields and soil properties, indicates that in a semi-arid Mediterranean irrigated field where rock fragments are present, the possibility of using NT with a rationalized nitrogen fertilization could reduce environmental risks and costs in inputs without decreasing yields or soil quality.

Finally, the difficulties observed for plants emergence under NT, which can be related to the use of direct seeders over a soil with rock fragments, can be overcome by selecting machinery specifically prepared for this type of soils combined with the selection of crops with an elevated tillering potential.

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Chapter IV

Implications of rock fragments for soil organic C and soil quality evaluation: Assessing changes in a gravelly irrigated soil following no till adoption

CHAPTER IV

Implications of rock fragments for soil organic C and soil quality evaluation: Assessing changes in a gravelly irrigated soil following no till adoption.

ABSTRACT

Stony and gravelly soils have been usually considered marginal for agriculture because the presence of rock fragments at the soil surface can limit both crop development and soil management. However, these soils are increasingly being converted from less intensive land uses to agricultural crop production, including their conversion to irrigation. Conservation tillage techniques may be adopted in these soils with the objective of increasing their protection against degradation, and therefore to enhance their quality. Nevertheless, the assessment of changes in management on soil quality in these soils can be troublesome. Total, particulate and mineralizable organic C, total N and their stratification ratios with depth were monitored under conventional and no-tillage systems in an experimental field recently converted from dryland to irrigation, on a soil with 40% of rock fragments on average. The implications of the presence of rock fragments for soil quality and also for converting C and N contents to area units in these soils was evaluated. Gains of up to 10 Mg C ha^{-1} were observed in the tilled layer (0-30 cm) only two years after the onset of irrigation, with no differences between treatments. In addition, no-tillage contributed to increase the presence of organic matter at the topsoil layer (0-5 cm). Carbon and N contents remained significantly higher at the surface with no till, but their stratification ratio was also affected by the correction of the rock fragment content. The labile organic fraction stood as a sensitive soil quality indicator to management changes, even after rock fragments content correction. Different methodologies used for rock fragment content assessment led to overestimations of up to 20% of organic C stocks.

The assessment of changes induced in soil by changes in management such as no tillage adoption and irrigation needs careful consideration of the soil rocks fragment content.

INTRODUCTION

Rock fragments (the coarse inorganic fraction > 2 mm) are frequently found as a part of the soil volume (Rytter, 2012) in many areas. When this fraction represents more than 15% of the soil volume, it is considered to affect soil functioning, and has to be considered as a “texture modifier”. Their importance in this sense depends on both the rock fragment content and their size-distribution (Schoeneberg et al., 2002).

These soils are widespread in many areas like the Mediterranean region, where they cover more than 60% of the land (Poesen and Lavee, 1994). It is also possible to find this type of soils in many other parts of the world, such as West Africa (Jones et al., 2013), Chile, Peru, Venezuela, Brazil or Central America (Gardi et al., 2014), or many regions of the United States (Throop et al., 2012).

Soils with rock fragments are usually less productive than other soils. Their presence at the soil surface can limit both crop development and soil management by impeding tillage (Soil Survey Division Staff, 1993). Besides, there are some drawbacks of these soils issuing from the fact that the volume of rock fragments reduces the space that would be occupied by the fine earth, limiting soil properties inherent to the latter. In semi-arid regions, they have been usually considered marginal soils for agriculture since long ago (Soil Science Society of America, 1984).

The interest in these soils is however gaining importance because they are increasingly being converted from less intensive land uses to agricultural crop production to satisfy the increasing demand for food, fibber and renewable energies. This includes their conversion from dryland to irrigated agriculture. Irrigation has in fact expanded rapidly in the last decades, reaching 20% of the total cultivated area (FAO, 2011).

The introduction of irrigation implies greater primary productivity, and can help to overcome the natural limitations of soils with rock fragments. As a result of greater organic C inputs to the soil from crops, compared to drylands, soil organic C stocks can increase, as reported by Gillabel et al. (2007) and Denef et al. (2008).

Conservation agriculture (CA), like minimum tillage or no tillage (NT), is also known for maintaining or improving soil properties like soil organic carbon (SOC) stocks at the surface layer, water retention and fertility. The adoption of CA in semi-arid regions has been successful, among other reasons, due to its ability to improve the soil water balance reducing evapotranspiration, and increasing the soil water storage capacity (Díaz-Zorita and Grove, 2002; West and Post, 2002; Bescansa et al., 2006; Moreno et al., 2006; Imaz et al., 2010; Varvel and Wilhelm, 2011). In irrigated agroecosystems this advantage is reduced, as water is not a limiting factor for soil production. The introduction of CA can be however justified by its ability to protect the soil against erosion and degradation, and therefore to enhance its quality while decreasing nutrients losses by leaching (Arroyo Garcia et al., 2012; Fernández-Romero et al., 2016).

The interaction of CA and soils with rock fragments has been however seldom addressed, and its adoption can be challenging in this context (e.g. Schwilch et al., 2015).

Soil quality has been defined as the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen et al., 1997). This definition has evolved in time, and at present, the ability of soils to provide different services such as the ones included in the definition, and others such as the preservation of biodiversity, is acknowledged to be linked to both their natural capital and soil properties. This means that the provision of the so-called soil ecosystem services in agroecosystems depends on the interaction of the soil natural characteristics, the farming practices and soil management (Dominati et al., 2010; Adhikari and Hartemink, 2016).

In the case of soils with rock fragments, their proportion and size-distribution is an intrinsic characteristic that can significantly affect the ability of soils to function. Two significant questions arise when considering soil quality assessment in this sense. First, the validity of indicators known to be adequate in soils without rock fragments. Second, the necessity of finding adequate approaches for considering the content of rock fragments when translating the concentration of soil components such as organic matter, water or nutrients into amounts or stocks of such components.

In relation to soil quality indicators, they should be easy to measure, able to reflect short and long term changes in soil properties, sensitive to land use and accessible to many users (Doran et al., 1996). Soil organic matter content (SOM) is in this sense a soil attribute commonly used to measure soil quality (e.g. Franzluebbers, 2002). Its assessment is not straightforward (Sojka and Upchurch, 1999), because SOM contents in some soils able to produce high crop yields in non-temperate regions, may be lower than those attributed to good soil quality in temperate regions. One example of this could be soils in semi-arid regions with low average contents in SOM but high productivities (Álvaro-Fuentes et al., 2008a; Imaz et al., 2010; Rodriguez Martín et al. 2016), or under irrigation.

Other well-known indicators used in soils without rock fragments are the stratification ratios of SOM and N with depth, the interaction between SOC and N in a soil represented by the C:N ratio (Franzluebbers, 2002; Aziz et al., 2013; Fernández-Romero et al., 2016), the concentration of particulate organic matter (POM), which is known to be more sensitive to soil management changes than SOM (Six et al., 2002; Álvaro-Fuentes et al., 2008a; Ladoni et al., 2015), and the soil mineralizable carbon, which is a measure of the degree of biodegradability of SOM, resulting from its chemical composition and/or its physical availability to decomposers (Ladoni et al., 2015).

These quantitative indicators have been successfully used to evaluate soil quality under different tillage systems in rainfed semi-arid land for assessing certain soil functions such as the protection against erosion or biomass production (e.g. Virto et al., 2007; Imaz et al., 2010). The interaction of rock fragments, which may show a heterogeneous distribution through the soil profile, with these indicators, is not well understood, although they are known to interfere with soil processes such us organic matter cycling or hydraulic properties (Stendahl et al., 2009).

In the case of soils recently converted from rainfed agriculture to irrigation, an added source of uncertainty is the fact that irrigation can change the incorporation and mineralization dynamics of crop residues into the soil organic pool, and modify their distribution within the soil structure in the short time (Apesteguía et al., 2015). This is in agreement with the observations of Zhou et al. (2016), who reported greater mineralization rates with the adoption of irrigation.

In relation to the quantification of stocks of different soil components, the transformation of SOC to a spatial basis is a significant source of variability (Throop et al., 2012; Rodríguez Martín et al., 2016), and becomes particularly troublesome in soils with rock fragments, because sampling methods may underestimate the amount of rock fragments present in the soil, and accurate determinations of the soil bulk density can be difficult (Rytter, 2012; Throop et al., 2012). This is especially relevant because a correct assessment of this characteristic is needed for low estimation errors, especially in studies aiming at scaling up soil properties and the soils response to changes in management.

In this research, we aimed at addressing the implications of using different approaches for evaluating the effects of soil management changes in a soil that contains rock fragments. That for, we conducted a study in an experimental field recently converted to irrigation with the objectives of (i) assessing the short-term (2 years) effect of the introduction of NT practices together with irrigation on SOC content and soil quality indicators in the fine earth, (ii) evaluating the adequacy of the quality indicators studied for soils with rock fragments, and (iii) assessing the implication of using different methodological approaches for calculating SOC stocks in these type of soils.

MATERIALS AND METHODS

Soil and experimental site. This study was conducted on an experimental field located in Olite (42º 26´ 50,10´´N; 1º 38´ 28´´W), in the NE of Spain. The climate in the area is Mediterranean (Csa) in the Köppen classification (Kottek et al., 2006). The soil of the experimental field was a sandy-clay loam (640 g kg^{-1} sand, 140 g kg^{-1}

silt and 220 g kg^{-1} clay) *Petrocalcic calcixerept* (Soil Survey Staff, 2014) developed on a terrace of the Cidacos river. A specific characteristic of these types of terraces is a high rock fragment content and the presence of a petrocalcic horizon at 30-35 cm. Rock fragments were predominantly sandstones and calcrete form the petrocalcic horizon brought up by tillage. The predominant size distribution, according to their effective diameter, was similar through the soil profile comprising fractions from 20 mm to 60 mm, classified as medium gravel by FAO (2006). The content of carbonates was high (250-270 g kg^{-1} $CaCO_3$ in the upper Ap horizon) and the slope in the field was negligible.

Experimental design. The study was established in a field that had been converted to irrigation one year before the beginning of the experiment. It was previously used for rainfed cereal cropping for decades. A randomized split-plot design with six replicates was adjusted to the field's sprinkler irrigation system (15 x 18 m). Plots had a dimension of 6 x 13 m. Two tillage treatments were compared. Conventional tillage (CT) consisted on various chisel-ploughing operations to a depth of 15 cm that incorporated crop residues into the soil, followed by seedbed preparation using a cultivator. No till (NT) consisted on direct seeding maintaining crop residues on the soil surface. The experiment was conducted during three years. The first year of the experiment is denoted hereafter as “year 0”, and the following years as “year 1” and “year 2”. In order to avoid heterogeneities due to previous management, the first year of the study (year 0) was considered as the baseline of the experiment. During this year, all the plots were managed with CT as described above. The crop rotation during the three years of the study (years 0, 1 and 2) was: sorghum (*Sorghum vulgare* L.), winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.), respectively. Crops were managed according to the regular practices in the area except for the tillage treatments.

Collection of samples and methods of analysis. Within each plot, in order to obtain a representative elementary volume “REV” (Bear, 1972) samples were taken by collecting a large volume of soil from pits dug at the at 0-5, 5-15 and 15-30 cm depths. Samples for soil properties analysis were collected every year in spring. In year 0, three replicates were collected for every depth and values obtained were used as the baseline of the experiment. During each of the following years (year 1 and year 2), a total of 36 samples were taken, six replicates for every treatment and depth. Three randomized soil samples were used to make a composite sample for each treatment, layer and replication.

Sample material was air-dried and sieved to pass a 2 mm mesh and thoroughly homogenized for its analysis. SOC from the < 2 mm fraction was determined by wet oxidation (Walkley-Black, Tiessen and Moir, 1993) due to the elevated carbonate content. The particulate organic matter fraction (POM) was isolated by the method described in Virto et al. (2007) where 10 g of air-dry soil were dispersed and sieved for collecting the organic matter fraction > 53 μm. Organic C concentration in this fraction was measured by wet oxidation after grinding the POM fraction to a powdery consistency. The Kjeldahl digestion method was used to analyse total N from the samples. Mineralizable soil C was determined in soil samples from year 2 of the study for the 0-5 and 5-15 cm depths. 20 g of air-dried and sieved (< 2 mm) soil were moistened with deionised water at 55% of their field capacity and placed inside a jar together with 10 ml of NaOH 0.25N trap for respired CO_2. Samples were pre-incubated during 7 days. After that time the incubation was carried out during 21 days at 30 ºC and on days 1, 7, 14, and 21 the traps were replaced. Traps removed from the jars were titrated with HCl 0.1N after adding $BaCl_2$ 0.5N in order to determine the C evolved as CO_2 (C-CO_2) as explained by Virto et al. (2007).

As an indicator of soil quality, the stratification ratio of SOC, N, C-POM and C:N with depth was calculated for the CT and NT treatments as proposed by Franzluebbers (2002) for the three years of the study. Soil components at 0-5 cm were divided by those at 15-30 cm. These horizons were selected because the top layer is the most influenced by management whilst the 15-30 cm horizon was below the chisel-ploughing tillage depth.

Soil bulk density was obtained at the onset of the study by using the excavation method (Blake and Hartge, 1986). The rock fragment content of the field made the core method unfeasible and the size of the plots impeded regular sampling for bulk density. Once the samples were excavated and removed from the soil, a plastic foil was placed on the hole and then filled with water to determine its volume. Soil bulk density resulted from dividing the sample mass by the volume occupied by water.

Crop development and yield were recorded during the three years of the experiment. Cumulative carbon inputs from crops to the soil were obtained for year 1 and year 2 by summing the above- and below-ground residues left in the soil by sorghum (year 0) and winter wheat (year 1). Despite the fact that during year 0 of the experiment all plots were managed with CT as described before, sorghum production and residues were collected and calculated respectively for every plot in order to have the specific amount of inputs left for the following CT and NT treatments in year 1.

Sorghum production was intended for biomass-based energy and the above-ground biomass (AGB) left after harvest was 8% of the total biomass produced. For calculating its below-ground biomass (BGB), the relation between aboveground biomass and BGB for maize (22%) was used, because IPCC (2006) guidelines do not specify a relationship between BGB and AGB for sorghum, and maize is the crop with more similitudes in root development. Winter wheat AGB was calculated for each plot from the harvest index and the grain harvested as explained by Apesteguia et al. (2015), subtracting the quantity of straw removed from the field (70%). BGB was obtained by applying the IPCC (2006) relationship between AGB and BGB for wheat (24%). Carbon concentration of biomass residues was considered to be 42% (Virto et al., 2012).

Rock fragments assessment. In order to verify the homogeneity of rock fragments in the experimental field, an analysis of the rock fragments content was carried out for every tillage treatment plot and depth (0-5, 5-15 and 15-30 cm) by sampling a REV as explained before. Large rock fragments were firstly separated by hand and weighted. The remaining material of each sample were air-dried and sieved through a mesh of 2 mm. Sample material > 2 mm was immersed in a sodium hexametafosphate solution in order to disaggregate the fine earth attached to rock fragments, washed and oven-dried at 105 ºC. The gravimetric content of rock fragments was calculated by summing the mass of all rock fragments contained in the sample and reporting it to the total sample mass. The volume of the rock fragments was determined by the water displacement of their mass. Volumetric contents of rock fragments were obtained by applying equation 1, as described by Poesen and Lavee (1994):

$$R_v = R_m \times BD_{soil} / D_{rock\ fragment} \qquad \text{Equation 1}$$

where R_v ($m^3\ m^{-3}$) is the volumetric content of rock fragments, R_m ($g\ g^{-1}$) is the rock fragment content by mass units, BD_{soil} is the soil bulk density ($g\ cm^{-3}$) and $D_{rock\ fragment}$ is the rock fragment density ($g\ cm^{-3}$).

In order to evaluate how the content of rock fragments affected soil quality evaluation, after analysing the stratification ratio of the properties inherent to the fine earth, the same ratio was calculated using their content in the whole soil (including rock fragments) instead of the fine earth, and both data were compared. For that purpose, the content of soil components were obtained by using the gravimetric content of rock fragments for the different soil depths and tillage treatments, as shown in equation 2 (Eq. 2):

$$X_{soil}\ (g\ kg^{-1}{}_{soil}) = X_{fine\ earth}\ (g\ kg^{-1}) \times \text{Rock fragment content}\ (g\ g^{-1}) \qquad \text{Eq. 2}$$

where X_{soil} is the component concentration in the whole soil and $X_{fine\ earth}$ is the concentration of that component in the fine earth directly obtained from the chemical analysis.

In soils with rock fragments such as the one studied here, the conversion of SOC or other soil components content to units of area is critical. The assessment of the implications of choosing one method or another when calculating SOC pools was carried out by comparing results obtained after applying different equations for SOC stock calculations. Equation 3 displays the method proposed by Throop et al. (2012). In this work, the authors developed an alternative hybrid method for calculating the bulk density of soils with rock fragments by using the mass of the fine earth contained in the sample and its total volume, including the rock fragments.

$$SOC = C_{FE} \times D \times BD_{Hybrid} \qquad \text{Equation 3}$$

where SOC is expressed as Mg ha^{-1}, C_{FE} is the SOC content (g 100 g^{-1}) in the fine earth, D is the layer thickness (m) and BD_{Hybrid} (g cm^{-3}) is the bulk density obtained by dividing the mass of the fine earth by the total volume of the soil, including the rock fragments. The use of this equation is in consonance with other authors, such as Hedley et al. (2012) or Rytter (2012), who stressed out the importance of only considering the fine material that a soil contains when calculating carbon and nutrient stocks. Results from this equation were compared to those obtained by equation 4 which is widely used for SOC estimations (e.g. Rodriguez Martín et al., 2016). In equation 4, the bulk density of the whole soil (obtained directly from the excavation method) is considered and a simple correction for the rock fragment volume is applied.

$$SOC = C_{FE} \times D \times BD_{soil} \times (1 - S) \qquad \text{Equation 4}$$

where S is the volumetric content of rock fragments (m^3 m^{-3}).

Statistical analysis. Data are presented as ± standard error of the mean for every soil property. Comparison between treatments was carried out by using the univariate linear model (ANOVA). Homogeneity of variances was verified by the Levene test. Duncan test was selected for the post-hoc analysis. Significant differences were based on a probability level of $p < 0.05$ unless otherwise indicated. All statistical analyses were performed using the SPSS 18.0 software (SPSS Inc. 2009).

RESULTS

Crop yield and SOC, C-POM and N contents in the fine earth. Although at year 0 all plots were managed under CT, biomass production and residues were collected independently for subsequent CT and NT calculations of C inputs in each treatment (Table 1).

Table 1. Carbon inputs and biomass production per tillage treatment during the years 0 and 1 of the experiment. During year 0 all plots were managed under CT, however sorghum inputs and production are shown separated from CT (conventional till) and NT (no till) plots for subsequent calculations.

	Inputs (Mg C. ha^{-1} yr^{-1})		Crop production (Tons. ha^{-1} yr^{-1})	
	CT	NT	CT	NT
year 0 (sorghum)	1.93a ± 0.07	1.87a ± 0.06	14.34a ± 0.68	13.92a ± 0.80
year 1 (wheat)	1.19a ± 0.06	1.06b ± 0.03	5.06a ± 0.22	4.65a ± 0.25

Different letters indicate significant differences (p-value<0.05) between treatments in the same year. The number of samples is 6 per treatment.

Crop production was similar under both management systems. However, winter wheat C inputs among treatments were higher for CT at $p < 0.10$. Therefore, cumulative C inputs from years 0 and 1 were higher in CT plots ($p < 0.10$). The proportion of this cumulative organic C incorporated into the soil by the soil SOC increment from year 0 to year 2 was not significantly different. The conversion value of C inputs to SOC under NT was 47.45 ± 10.65 g of C input / 100 g soil in comparison with 34.72 ± 3.61 g of C input / 100 g for the CT treatment.

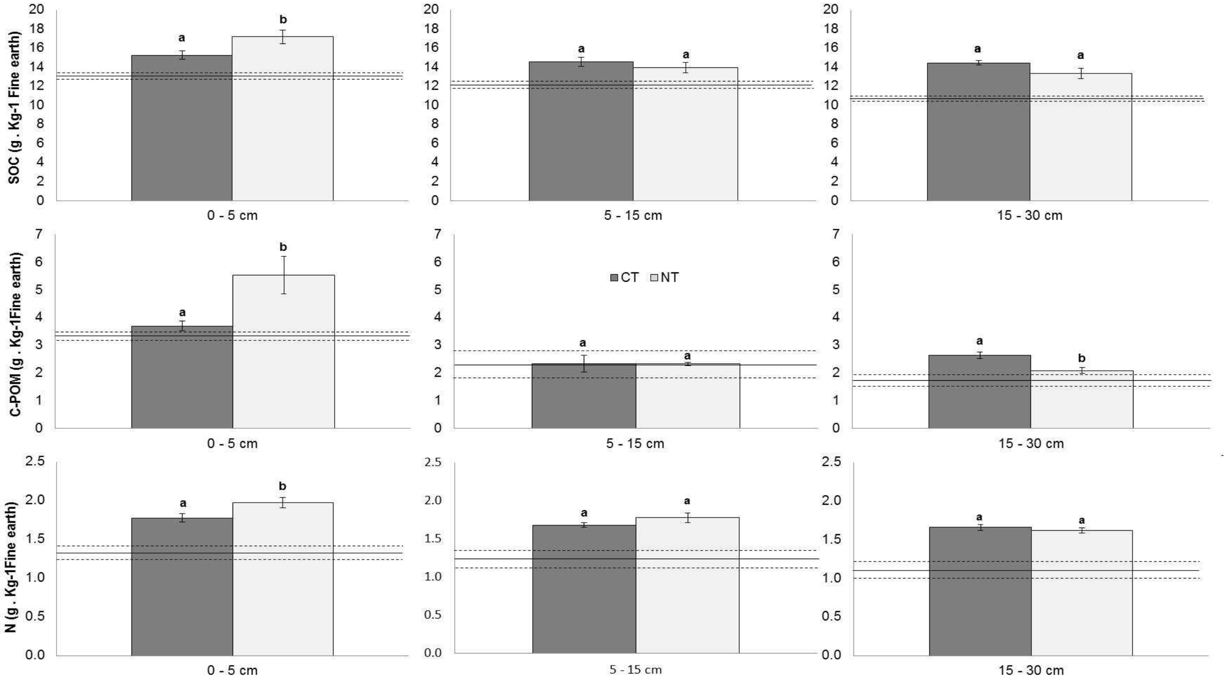

Figure 1. Content of SOC, C-POM and N in year 2 for the different tillage treatment and depth referred to the fine earth. The continuous lines of the graphs depict values of SOC, C-POM and N during year 0 for these depths with their errors (discontinuous lines). CT: conventional till; NT: No till. Different letters indicate significant differences between tillage treatments. The number of samples is 3 per treatment in year 0 and 6 per treatment in year 2.

Figure 1 shows the significant increase of soil organic C, C-POM and total N contents from year 0 (values depicted as continuous lines and errors depicted as discontinuous lines) to year 2 for both treatments. This result was more noticeable for NT at the 0-5 cm depth. In addition, NT values of SOC, C-POM and N in year 2 decreased with increasing soil depth. Differences between depths in the CT treatment were only found for C-POM, with greater values in the 0-5 cm depth.

Table 2 shows the evolution of the stratification ratio of SOC, C-POM, N and the C:N ratio from year 0 to year 2 in the fine earth. Values for NT were significantly higher for all the studied parameters. Besides, the evolution was more noticeable for C-POM, which showed the highest increase since year 0.

Table 2. Stratification ratio for SOC, C-POM, N and C:N ratio for years 0-2 and the different tillage treatments for the fine earth. CT: conventional till; NT: no till.

	CT	NT
SOC Baseline year 0	1.19 ± 0.05	
SR SOC year 1	1.23a ± 0.06	1.14a ± 0.08
SR SOC year 2	1.06a ± 0.03	1.29b ± 0.04
C-POM Baseline year 0	2.02 ± 0.15	
SR C-POM year 1	2.13a ± 0.16	2.04a ± 0.18
SR C-POM year 2	1.43a ± 0.13	2.67b ± 0.31
N Baseline year 0	1.19 ± 0.05	
SR N year 1	1.23a ± 0.03	1.25a ± 0.03
SR N year 2	1.07a ± 0.03	1.21b ± 0.03
C:N Baseline year 0	1.00 ± 0.01	
SR C:N year 1	1.00a ± 0.04	0.91a ± 0.07
SR C:N year 2	0.99a ± 0.02	1.06b ± 0.02

Different letters indicate significant differences ($p < 0.05$) between treatments. The number of samples is 6 per treatment except for year 0 that is 3.

Finally, another index of soil quality analysed for the fine earth was respired CO_2-C at incubation. Figure 2 portrays the results for the 0-5 and 5-15 cm depths, expressed as cumulative µg CO_2-C (a), and µg CO_2-C per mg of soil SOC (b). The cumulative respiration indexes (a and b) were significantly higher in NT samples from the 0-5 cm soil depth, compared to the rest of samples. The mineralization peak was achieved at the beginning of the incubation. Right after that, mineralization rates were stabilized and remained almost constant until the end of the incubation.

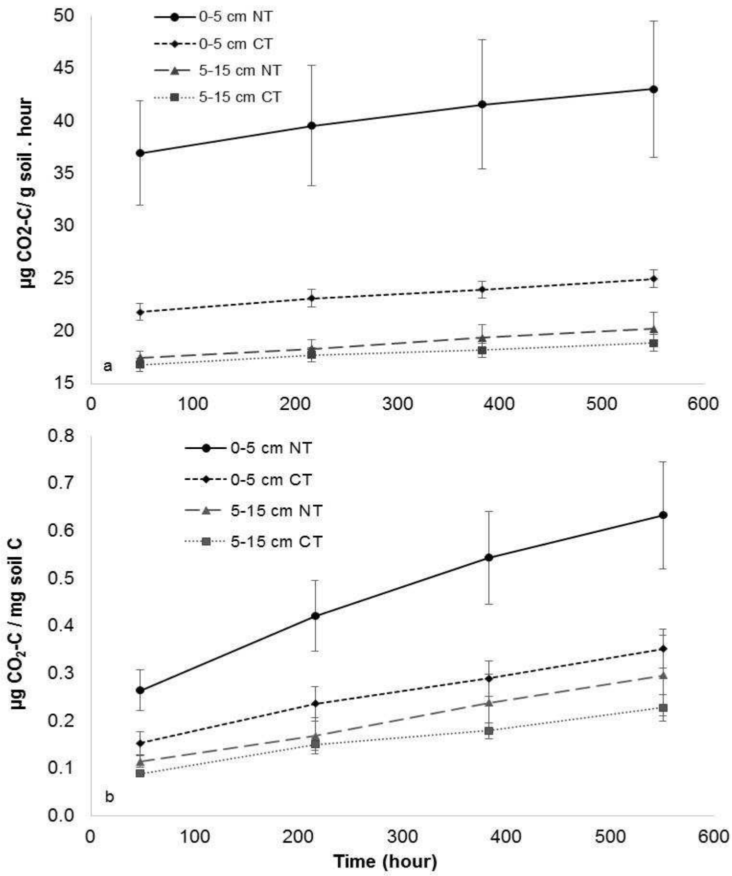

Figure 2. Data from organic matter mineralization accumulated during 21 days (a) and ratio of OM per mg of soil accumulated during 21 days (b) for the different tillage treatments and depths referred to the fine earth. CT: conventional till; NT: no till. The number of samples is 6 per treatment.

Table 3. Content of rock fragments per tillage treatment and depth (g 100 g^{-1}). CT: conventional till; NT: no till.

	Depth (cm)	CT	NT
% Rock fragments	0 – 5	52.54a ± 2.62	50.95a ± 3.23
	5 – 15	39.09a ± 1.73	39.36a ± 2.62
	15 – 30	37.07a ± 1.67	40.84a ± 2.68

Different letters indicate significant differences ($p < 0.05$) between treatments in the same row. The number of samples is 6 per treatment.

Rock fragment content assessment. Rock fragment content was uniform in the field, and did not show significant differences with regard to tillage treatments. However, this content varied with depth (Table 3). It was higher at the soil surface (0-5 cm) compared to the other two depths, for both treatments.

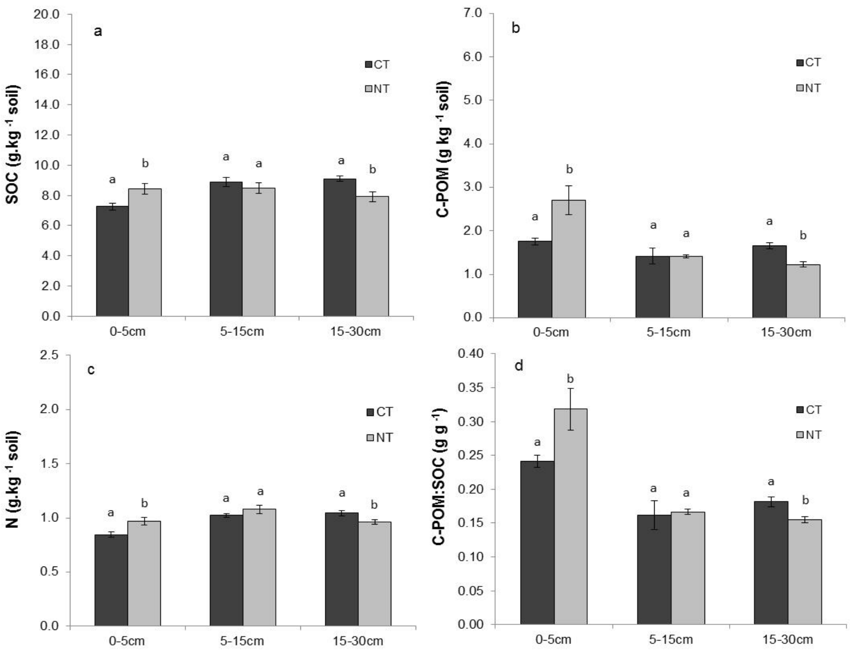

Figure 3. Content of SOC (a), C-POM (b) and N (c) and ratio C-POM:SOC (c) in year 2 for the different tillage treatment and depth after rock fragment content correction. CT: conventional till; NT: no till. Different letters indicate significant differences between tillage treatments. The number of samples is 6 per treatment.

The effect of rock fragment content in the vertical distribution of soil properties was studied. As the proportion of rock fragments in the soil was not homogeneous with depth (Table 3), it was expected to play an important role when analysing the stratification ratios of the soil components.

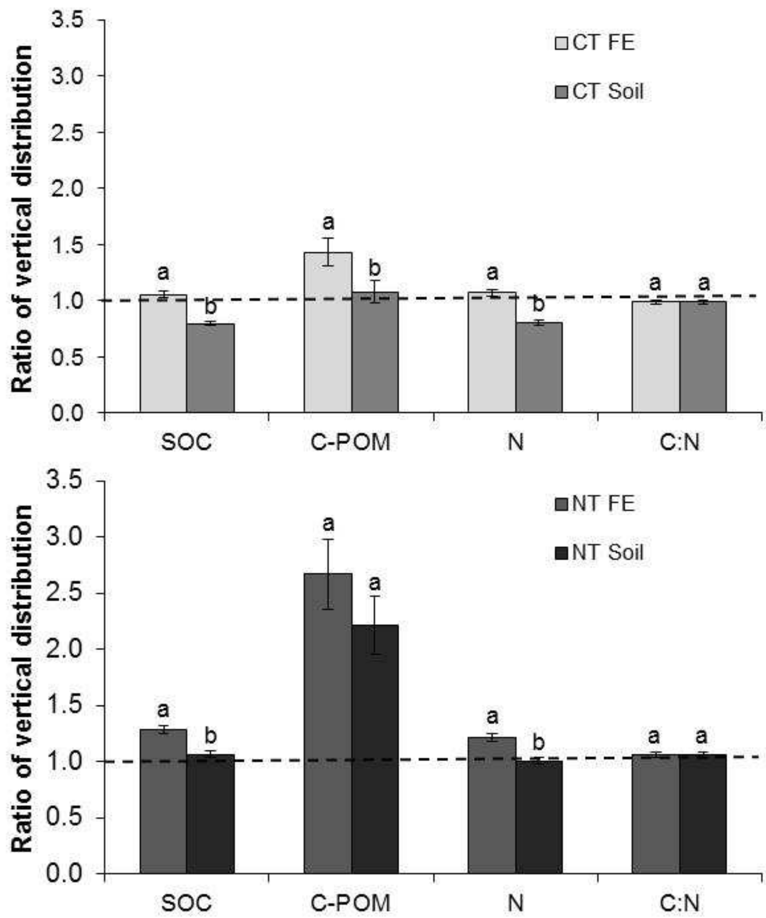

Figure 4. Stratification ratio of SOC, C-POM, N and C:N for year 2 and different tillage treatments for the fine earth (FE) and after rock fragment content correction (Soil). CT: conventional till; NT: no till. Different letters indicate significant differences between treatments. The number of samples is 6 per treatment.

The content of SOC, C-POM, N at the upper 5 cm of the soil was reduced drastically after correction by equation 2. The reduction at the

5-15 cm and 15-30 cm was 10-15% lower. Therefore, the ratios of their distribution through the soil profile were reduced (Figure 4). Plots under NT continued showing a higher content of SOC, C-POM and N at the topsoil layer because the rock fragment content was similar between tillage treatments. SOC:C-POM and C:N are ratios and they were therefore not affected by the correction of the rock fragment content.

The implications of considering only the fine earth of a soil with rock fragments when calculating stocks (equation 3) or the use of a simple correction for the volume that these rock fragments occupy (equation 4) are shown in Table 4. Values of SOC stocks calculated for year 2 with the hybrid method (47.9 ± 1.1 Mg C ha^{-1}) were higher than the baseline SOC stock at year 0 (37.9 ± 0.7 Mg C ha^{-1}). As expected, SOC stocks values calculated using equation 4 were also higher for year 2 compared to year 0 but reached values of 57.2 ± 1.1 Mg C ha^{-1}. Same differences were found for N.

Table 4: SOC and N stock for years 0 and 2 using the different methodologies described by equations 3 and 4. CT: conventional till; NT: no till.

Stock (Mg. ha^{-1})	Depth (cm)	Year 0		Year 2	
		Hybrid method	Simple correction method	Hybrid method	Simple correction method
SOC	0 - 5	6.0aA ± 0.5	7.7aB ± 0.7	6.9aA ± 0.2	8.9aB ± 0.3
	5 - 15	13.3aA ± 0.4	15.9aB ± 0.5	15.8aA ± 0.5	19.0aB ± 0.6
	15 - 30	18.6aA ± 0.6	21.9aB ± 0.7	25.1bA ± 0.5	29.3bB ± 0.5
	0 - 30	37.9aA ± 0.7	45.5aB ± 0.8	47.9bA ± 1.1	57.2bB ± 1.3
N	0 - 5	0.6aA ± 0.0	0.8aB ± 0.0	0.8bA ± 0.0	1.04bB ± 0.0
	5 - 15	1.4aA ± 0.1	1.7aB ± 0.1	1.8bA ± 0.0	2.19bB ± 0.1
	15 - 30	1.9aA ± 0.1	2.2aA ± 0.1	2.9bA ± 0.1	3.4bB ± 0.1
	0 - 30	3.9aA ± 0.2	4.7aB ± 0.3	5.5bA ± 0.1	6.6bB ± 0.1

Different letters indicate significant differences ($p < 0.05$) between year 0 and year 2 for the specific depths and methodology studied. Different capital letters indicate significant differences ($p < 0.05$) between methodologies for the specific year and depth. The number of samples is 6 per treatment.

Results from equation 4 were systematically and significantly higher than results from the hybrid method (equation 3). In this case, for a soil with an average mass of rock fragments of 40% throughout the soil profile, the simple correction led to estimations of SOC, C-POM and N stocks around 20% higher than those obtained with the hybrid method.

DISCUSSION

Soil quality assessment based on fine-earth characteristics. The adoption of NT compared to CT in a study with simultaneous adoption of irrigation had consequences in most of the soil parameters considered.

Since the onset of the field study at year 0, the contents of SOC, C-POM and N in the fine-earth increased significantly in both management systems after only two years (Figure 1). This was expected following the introduction of irrigation, as the increased crop productions led to a rise in C inputs to the soil (Gillabel et al., 2007; Denef et al., 2008). Apesteguia et al. (2015) confirmed that irrigation activated C accumulation, but they remarked that it also enhanced its decomposition, as observed by De Bona et al. (2008) in subtropical conditions. However, Kong et al. (2009) reported that C and N pools under irrigation did not change from dryland values regardless of the cultivation system, but they conducted the study only 1 year after the adoption of conservation tillage practices. Our results suggest that in the studied conditions and soil, the observed higher inputs resulted in a net increase of SOC in only two years.

This increase of SOC, C-POM and N was more noticeable for the NT treatment at the topsoil layer because of crop residues accumulation under this management combined with the lack of soil disturbance. In comparison, CT plots showed a more homogeneous distribution throughout the studied soil profile because residues where incorporated at lower depths. These results for organic matter and N redistribution with depth upon the adoption of NT are a common situation in NT systems (Angers and Eriksen-Hamel, 2008), and have been described in many non-irrigated soils (Franzluebbers, 2002; Moreno et al., 2006, Álvaro-Fuentes et al., 2008b; Varvel and Wilhelm, 2011; Aziz et al., 2013; Alvarez et al., 2014). The difference in relation to previous studies in the area (e.g. Virto et al., 2007) is that this stratification was observed after a medium-long period of time (more than 5 years), whereas it was observed in our study already 2 years after the implementation of NT. Therefore, the introduction of NT together with irrigation in a previously rainfed agrosystem accelerated the accumulation of SOC at the upper soil layer in a shorter period of time than previously reported. As Franzluebbers (1998) pointed out, the effectiveness of NT for incorporating SOC can be limited by less optimal conditions for residue decomposition when it is left at the soil surface. In semiarid conditions, water scarcity during the period at which crop residues are left because of low precipitations can lead to reduced rates of C accumulation, as reported by some authors like Fernández-Romero et al. (2016) or Rodriguez Martín et al. (2016). These limitations can be overcome when the transformation to irrigation takes place. In addition, as suggested by Melero et al. (2012), coarse textured soils usually have lower aggregation degrees, and therefore a higher response capacity for binding agents under NT systems, which could also explain the increment in such a short period of time.

Under the light of these results, if soil quality assessment was only based on SOC content, both tillage systems could be considered as similar because there were no differences in the total SOC content in the fine earth within the 0-30 cm depth at year 2. This had also been observed in the region in mid-term studies such as Álvaro-Fuentes et al. (2008a), who did not found differences on SOC contents between NT and CT after more than 15 years of tillage testing when the whole studied depth (0-40 cm) was considered.

The stratification ratios studied showed a different evolution with time depending on the tillage system (Table 2). Under NT, the accumulation of SOC, C-POM, N and C:N at the upper soil layer increased significantly from year 0 to year 2 compared to CT. Following Franzluebbers (2002), this can be seen as NT displaying a better soil condition that leads to an improvement of water movement and infiltration, lower loss of nutrients, more stable aggregates and more biological activity.

Stratification ratio values were < 2 (except for C-POM), similar to those found by some authors (Melero et al., 2012; Alvarez et al., 2014), but lower than values found in other studies (Díaz-Zorita and Grove, 2002; Franzluebbers, 2002; Fernández-Romero et al., 2016).

Particulate organic matter, evaluated here as C-POM, has been usually described as an early detector of soil quality changes, and observed to increase fast when NT is adopted (e.g. Imaz et al., 2010). It represents the most labile fraction of SOC. In this study, the highest ratio of C-POM-to-SOC was found at the 0-5 cm depth for NT (Figure 3). This, together with a higher value of the C:N ratio at the topsoil layer, and the observed higher respiration rates for this treatment and depth (Figure 2), indicated that the studied soil was sensitive to tillage changes. The use of C-POM as a fast indicator of soil quality in irrigated agrosystems is therefore supported by these results.

From the point of view of soil quality understood as the ability of the soil to accomplish a number of functions in the agrosystem, our results suggest that the adoption of a conservation management under irrigation could contribute to increase the presence of organic matter at the soil surface in the short term, and therefore can be seen as an adequate tool to grant the supply of soil services related to organic matter accumulation in the soil-atmosphere interface, such as the provision of food and raw materials, climate regulation or erosion and flood control (Adhikari and Hartemink, 2016).

Implications of rock fragments on SOC storage and soil quality assessment. Stony soils have a reduced quantity of fine earth and, therefore, a higher limitation for organic matter and nutrients accumulation than stone-free soils. This implies that, as Poesen and Lavee (1994) pointed out, the amount of inputs to the soil remain the same, but concentrated in the fine earth fraction. In our study, this could have been a factor contributing to detecting significant differences between tillage treatments on soil properties inherent to the fine material in a so short period of time.

Furthermore, the presence of rock fragments in proportions close to 40% on average in the studied soil allows for the necessary verification of the consistency of common analytical approaches and quality indexes described above for the fine earth, when used in soils that contain rock fragments.

Whilst many researchers report their results referred to the fine earth because rock fragments do not contribute to soil properties (Throop et al., 2012), results found in this study pointed out the importance of rock fragments correction for soil quality assessment. SOC, C-POM and N quantities were not only reduced notably when this correction was applied (Figure 3). In addition, the higher content of rock fragments at the soil surface than at deeper depths (Table 3) made the differences observed for the fine earth in the vertical distribution of soil components smaller when the correction for rock fragments was applied (equation 2). Therefore, rock fragments correction modified the picture of the vertical distribution of soil components.

In these conditions, we observed that the stratification ratio of C-POM was still > 2 and showed the highest difference between tillage treatments, while that of other soils components considered were less sensitive to changes in management (Figure 4). Thus, C-POM was confirmed not only as a premature indicator of soil management practices, but also as a reliable quality indicator for management changes in soils with rock fragments. C:N and C-POM:SOC ratios were not affected by the rock fragment content correction because they are the result of a quotient between two variables. This fact made them together with C-POM a good choice when analysing quality of soils with rock fragments.

On the other hand, when calculating stocks, data in Table 4 show the implications of using the two different approaches (equations 3 and 4) considered for the correction of bulk density in the studied soil. The use of the simple correction by the volume of rock fragments (equation 4) led to an overestimation of SOC stocks in this gravelly soil, in comparison to the hybrid method (equation 3). Because the overestimation is directly related to the volume of rock fragments, this problem would be accentuated with increasing rock fragment contents. The correction used in equation 4 accounts for the volume displaced by rock fragments, but assumes that the concentration of SOC corresponds to the whole soil mass. This agrees with Rytter (2012), who affirmed that neglecting or miscalculating the rock fragments volume present in the soil can lead to overestimations of C and N stocks. Besides, Schrumpf et al. (2011) pointed out a dominant contribution of rock fragments variability to the total C stock variance in soils with > 20% of rock fragments, being even more important than the own variability of SOC concentration values. They also reported a higher C stock variability as the rock fragment content increased. Also, Hedley et al. (2012) associated part of the variability observed in SOC stocks to the error derived from estimating the percentage of rock fragments.

Thus, an accurate correction of stocks by the volume of rock fragments needs either to correct the bulk density or the nutrients content. From a methodological point of view, this means that when dealing with soils that contain rock fragments, it seems of the greatest importance to clearly specify not only the sampling method used and the final content of rock fragments, but also the methodology applied to calculate stocks, to and clearly define whether variables are referred to the fine earth or to the whole soil volume (Hedley et al. 2012, Rytter 2012).

Finally, in relation to the values of SOC stocks measured using the hybrid method, they increased from 37.9 ± 0.7 to 47.9 ± 1.1 Mg ha^{-1} on average, from year 0 to year 2, for the whole studied depth (0-30 cm), with no differences between tillage treatments. These values were within the ranges reported by Lugato et al. (2014) for Mediterranean areas and Rodriguez Martín et al. (2016) in Spain. Hedley et al. (2012) also reported average SOC stocks of 49 Mg ha^{-1} on average at 0-30 cm in rainfed agricultural soils with a range of rock fragments volume from 5 to 70%, with a variability of ± 25 Mg ha^{-1}. These stocks were lower and more variable than in soils without rock fragments, which illustrates the importance of the consideration of rock fragments when scaling-up the results of short-term experiments in this type of soils.

CONCLUSIONS

The adoption of NT practices in a Mediterranean gravelly soil together with irrigation contributed to accelerate organic C accumulation processes at the soil surface, which is of special interest for many agricultural lands with limitations for crop production, such as soils with rock fragments.

In the studied conditions, C-POM stood out as a robust soil quality indicator, very sensitive to land management changes in a short period of time, but also adequate for soils with rock fragments and irrigated systems.

If stratification ratio is to be used as an indicator of soil quality for certain specific soil functions like biomass production, in the presence of rock fragments, an adequate assessment is needed. This implies that soil components should be referred directly to the whole soil volume, and not only to the fine earth.

In relation to the estimation of soil components stocks, there are methodological issues that should be addressed in soils with rock fragments. For example, the implications of C stocks overestimation can be of importance for studies that scale up soil properties to regional or national levels, and determine soil and agricultural policies based on C stocks.

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Chapter V

Effect of stoniness on the hydraulic properties of a soil from an evaporation experiment using the Wind and the Inverse Estimation methods

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CHAPTER V

Effect of stoniness on the hydraulic properties of a soil from an evaporation experiment using the Wind and the Inverse Estimation methods

ABSTRACT

Stony soils are distributed all over the world. The study of their characteristics has gained importance lately due to their increasing use as agricultural soils. The effect that rock fragments exert on the soil hydraulic properties is difficult to measure in situ, and is usually derived from the fine earth properties. However, corrections used so far do not seem accurate for all types of stony soils. Our objective was to assess the adequacy of estimating stony soil hydraulic properties from the fine earth ones by correcting the latter by the volume the rock fragments occupy. The validity of different approaches for estimating the hydraulic properties of a stone-free and a stony (40% rock fragments) soil was also assessed. The functions relating the soil hydraulic properties (θ-h, K-h-θ) were estimated by the Instantaneous Profile Method, the Wind method and by Inverse Estimation using data from an evaporation experiment where the soil water content and pressure heads were measured over time. Results from the evaporation experiment were compared to those obtained by applying the equation that corrects fine earth properties by the rock fragments volume. Wind and the Inverse Estimation methods were successfully applied to estimate soil water content and hydraulic conductivity from the stony soil experiment, except for some uncertainties derived from the limited range of suction in which the experiment was conducted. The application of the correcting equation resulted in a simplified approach that did not take into account the effect that the creation of lacunar pores by the presence of rock fragments in the soil likely exert on water flow processes. The unsaturated hydraulic conductivity values were higher than those inferred by the correcting equation at the wet range, but decreased much faster with decreasing pressure head. A new equation to calculate the water content of a stony soil where the influence of possible lacunar pores is proposed.

INTRODUCTION

Soils that contain rock fragments (particles > 2 mm of diameter) are usually denoted as stony soils. Over the last years, the interest on studying the effect that rock fragments exert on soil physical properties has grown because soils containing them are distributed worldwide. With the increasing demand for food, fiber and renewable energies, these soils are being converted from less intensive land use to agricultural crop production. In Africa, the Sahara, Sahel and most soils in the geological mantle in the west of the African continent are gravelly (Jones et al., 2013). Places with stoniness from 15% to 80% are predominant in Central America and many areas of Chile, Peru, Venezuela or Brazil also fall into this percentage (Gardi et al, 2014). Only in the Mediterranean region stony soils already occupy more than 60% of the land (Poesen and Lavee, 1994).

Rock fragments play an important role in soil water dynamics because they have an influence on the soil water content and the hydraulic conductivity (Cousin et al., 2003; Hlavácíková and Novák, 2014). This influence is complex and depends on the volume fraction that they occupy in the bulk soil, their geological origin and grade of weathering, their size and also their position in the soil (Cousin et al., 2003). Initially, the presence of rock fragments reduces the cross-sectional area through which water flows leading to lower hydraulic conductivities (Bouwer and Rice, 1984; Ravina and Magier, 1984; Brakensienk and Rawls, 1994; Ma et al., 2010; Novák et al., 2011). However, their existence can create new lacunar pores at the rock fragment-fine earth interface that could cause paths for preferential water flow and thus an increase in the saturated hydraulic conductivity (Sauer and Logsdon, 2002; Ma and Shao, 2008; Verbist et al., 2009). Besides, their presence may be able to change the total porosity and its distribution depending on their volume, size, shape and the type of soil studied (Gargiulo et al., 2016). Some rock fragments are even able to hold water depending on their origin (Constantz, 1995; Cousin et al., 2003). Under unsaturated conditions, a volume of water that enters a soil with rock fragments will cause a larger matric potential or soil water pressure head (h) increase than the same volume of water entering the same soil without stones. A more rapid increase in hydraulic conductivity might be expected for the soil with rock fragments than for the soil not containing them.

The knowledge of the hydraulic properties of soils with rock fragments is limited. The common sampling methods for obtaining undisturbed cores used in non-stony soils are impracticable when large volumes of rock fragments are present. Besides, large volumes of soil need to be sampled in order to obtain a representative elementary volume (REV; Novák et al., 2011). Inserting probes, access tubes or installing lysimeters in-situ turned out to be complicated without altering soil structure (Bower and Rice, 1984; Cousin et al., 2003; Ma et al., 2010; Coppola et al., 2013; Hlaváciková and Novák, 2014) and is nearly impossible in soils containing stones.

Due to these challenges, some authors have tried to derive the stony soils' hydraulic properties from those observed in the fine fraction of the soil (Bower and Rice, 1984; Ravina and Magier, 1984; Novák et al., 2011; Hlaváciková and Novák, 2014) but being corrected for the volume of rock fragments (Brakensiek and Rawls, 1994; Lal and Shukla, 2004). However, for certain types of soils, the existence of rock fragments can lead to complications in the derivation of hydraulic properties from non-stony soils (Bower and Rice, 1984; Ma et al., 2010). Due to discrepancies in the results the question remains whether a simple correction can be applied for different soil types, shapes and sizes of rock fragments and whether this correction would be valid over a wide range of soil water content (θ), from wet to relatively dry conditions (Khaleel and Heller, 2003).

Recent studies on stony soils have been focused on measuring infiltration rate and hydraulic conductivity (Sauer and Logsdson, 2002; Verbist et al., 2009, 2010 and 2012) or estimating the soil hydraulic properties by using soil water transport models (Baetens et al., 2009; Dann et al., 2009; Thoma et al., 2014).

Milczarek et al. (2006), Ma and Shao (2008), Ma et al. (2010), Yang et al. (2013) and Beckers et al., (2016), used repacked soil cores to study hydraulic properties or porosity of stony soils. Although they cannot reproduce soil structure, experiments based on repacked soils with a controlled volume of rock fragments help to derive a basic understanding on the impact of different degrees of stoniness on the hydraulic properties, test the accuracy of the estimation methods used to derive the soil hydraulic parameters and also evaluate the adequacy of estimating these soil properties by simply correcting fine earth hydraulic properties by the volume the rock fragments occupy. The results found in the literature show a different influence of stoniness in soil hydraulic properties depending on the specific characteristics of the soil (i.e., texture, organic matter) and stones used (i.e., geological origin, shape, size) and also the volume which the latter occupy (Cousin et al., 2003; Ma et al., 2010; Novák et al., 2011; Tetegan et al., 2011). The discrepant results could be also attributed to the lack of a reference method for measuring hydraulic properties in stony soils and the different assumptions made by the authors during calculations.

The evaporation method is a reliable and simple method to determine soil hydraulic properties, i.e., the soil water retention curve (θ(h)) and the unsaturated hydraulic conductivity (K) as a function of pressure head (h). It was developed by Wind (1969), modified and validated by Wendroth et al. (1993) and used in various ways, e.g., by Simunek et al. (1998a).

Another approach to analyse experimental data obtained in an evaporation experiment is the inverse parameter estimation technique. Inverse methods are based on a water transport simulation algorithm, such as the finite element solution of Richards' equation, e.g., HYDRUS (Simunek et al., 1998b). For simulating water transport, the soil hydraulic properties can be described according to van Genuchten (1980). The simulation is coupled with a parameter optimization algorithm. Knowing from the evaporation experiment the upper and lower flux boundary conditions, h at different depths and the total water storage S in the sample over time t, HYDRUS can be used to estimate soil hydraulic function parameters. If soils with and without rock fragments are measured and analysed, the impact of the volume fraction of these rock fragments on the hydraulic function parameters can be derived.

Overall, the way in which unsaturated soil hydraulic property parameters are affected by rock fragments, which is very necessary for water flow modelling, is still not well understood or quantified. Thus, for a given soil without rock fragments, it is not yet known how to adjust soil hydraulic property parameters if the same soil contains a defined volume of rock fragments. Therefore, the objectives of this study were to 1) test the validity of different approaches for estimating hydraulic conductivity functions and water retention characteristics experimentally from a silt loam from evaporation tests data, 2) demonstrate the applicability of the same estimation approaches to obtain hydraulic parameters in the same soil in the presence of rock fragments, and 3) test the validity of corrections applied to stony soils for estimating the soil water content and the hydraulic conductivity from the fine earth properties in the conditions of this study.

MATERIALS AND METHODS

Experimental design. Evaporation experiments were conducted in the soil physics laboratory of the Kentucky Agricultural Experiment Station, University of Kentucky, Lexington, to derive soil hydraulic property functions (θ-h, K-h-θ) from pressure head and water content observations over time and at three soil depths. Two soil columns of 18 cm length and an internal diameter of 10 cm were packed with air-dry silt loam soil (11.8 % sand, 70.3 silt, 17.9 clay, 3.97% organic matter) that had been passed through a 2 mm sieve. This soil was selected because it is commonly found in nature and does not exhibit volume changes with different water contents. The air-dry soil water content was 0.025 cm^3cm^{-3}. One of the two soil columns was packed entirely with sieved soil while the other one was repacked with sieved soil and rock fragments. The latter were distributed randomly and they occupied 40% of the total volume. The 40% volume of rock fragments was selected because this percentage falls inside the USBR arable land class number 3. From this point on, subsequent land classes (4, 5 and 6) show restrictions for irrigation purposes (FAO, 1985). Rock fragments were sub angular and sub rounded shaped, with an equivalent diameter of 2 - 6 cm and with a negligible water holding capacity. The particle density of the rock fragments was 2.65 g cm^{-3} and it was measured by water displacement of their mass. The cylinders were repacked under the premise of reaching a bulk density of 1.3 g cm^{-3} for the fine soil material. The soil column with rock fragments is further denoted as stony.

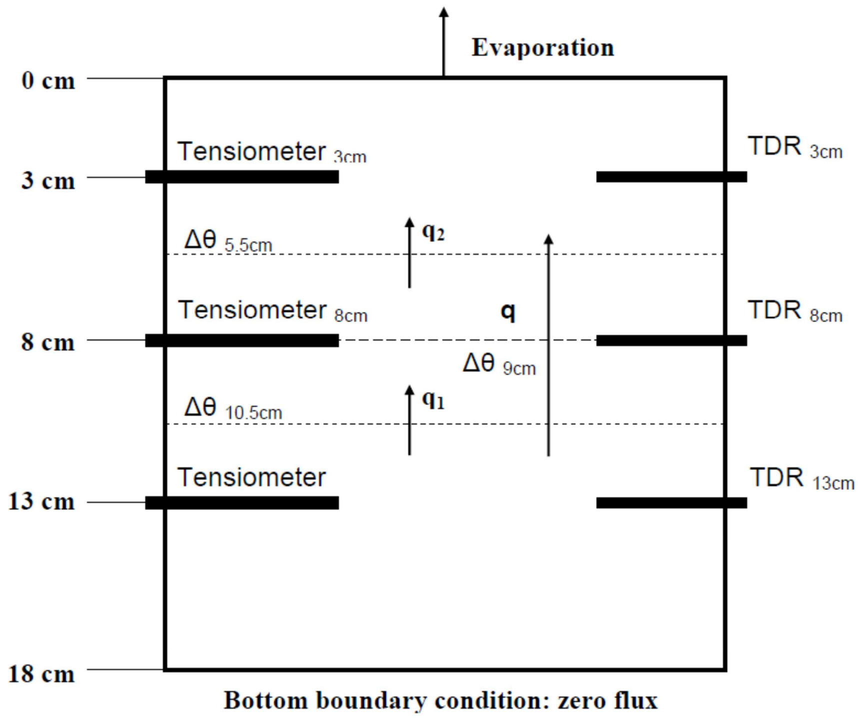

Figure 1. Experimental setup of the evaporation experiment. q, q1 and q2 are the upward water volume flux densities across the 8 cm, 10.5 cm and 5.5 cm boundaries, respectively.

Three electronic pressure transducer tensiometers were inserted horizontally in the soil columns at 3, 8 and 13 cm from the surface. The insertion length of the ceramic cup was 4 cm and the diameter 0.6 cm. The holes for the ceramic cups were drilled using a screw auger with a diameter slightly smaller than the ceramic cup's diameter to ensure good cup-soil contact. The pressure transducers (26PCCFA6D) had been calibrated before for a silty loam soil. In order to indirectly measure the soil water content, CS640 TDR probes, with a length of 7.5 cm, were installed in the soil columns at the same depths as the ceramic cups. As shown in Figure 1, the cylinder columns were divided into 3 different compartments, based on the depth center between two measurement depths, 0-5.5 cm depth, 5.5-10.5 cm depth and 10.5-18 cm depth.

Before the onset of evaporation, the soil column was placed on a porous plate that was connected to a hanging water column of 15 cm length. The cylinder was covered with a lid to avoid evaporation and hydraulic equilibrium was established at a pressure head of -15 cm at the lower boundary. For the evaporation experiment, the soil column was removed from the suction plate and placed on a Plexiglas plate that was deposited on a balance (10^{-2} g of precision). The balance was connected to a data logger and total mass was recorded once every hour for quantifying the amount of water evaporated. After that, the lid was removed from the top of the column. Evaporation continued until the upper tensiometer showed a pressure head reading close to -450 cm. No further measurements were taken preventing air entering in the tensiometer altering measurements. Soil columns were subjected to wetting-drying cycles prior the onset of the experiment in order to assure structural settlement.

Pressure head and water content pairs were logged every minute and further processed to be used as inputs for quantifying hydraulic properties of both soil columns.

Theory. The soil water content is a non-linear function of soil water pressure head that can be described by the model proposed by van Genuchten (1980):

$$\theta = \theta_r + (\theta_s - \theta_r) / [1 + (\alpha|h|)^n]^m \qquad \text{Equation 1}$$

where, θ_s is the saturated water content [L^3 L^{-3}], θ_r is the residual water content [L^3 L^{-3}], and α [L^{-1}], n and m (m = 1 – 1/n) are empirical fitting parameters describing the curve shape. The desorptive water retention curve obtained with the evaporation experiment was iteratively derived based on Wind´s method (1969), using a fourth order polynomial equation. The hydraulic conductivity (K) for each time interval was estimated following the procedure described by Wendroth et al. (1993). The hydraulic conductivity between the 0-8 cm depth and 8-18 cm depth compartments was calculated from the water flux across the 8 cm depth (q). Hydraulic gradients below a threshold value of 0.3 cm cm^{-1} were not considered for calculating K because of the precision of pressure transducer measurements (Wendroth et al., 1993). Data obtained from the experiment were fitted to the unsaturated hydraulic conductivity function expressed in terms of pressure head resulting from combining the Mualem (1976) model for predicting unsaturated hydraulic conductivity with van Genuchten's (1980) model:

$$K(h) = K_s \{[1 + |\alpha h|^n]^m - |\alpha h|^{(n-1)}\}^2 / [1 + |\alpha h|^n]^{m(\ell+2)} \quad \text{Equation 2}$$

where K_s is the saturated hydraulic conductivity and ℓ is a dimensionless pore tortuosity parameter that was assumed to be 0.5 as in many stony other soil studies (Baetens et al., 2009; Verbist et al., 2009; Hlavácikovà and Novák, 2014).

Some hydraulic properties of stony soils can be derived from the fine earth fraction's properties if the water retention capacity of rock fragments is assumed to be negligible. Using the equation proposed by Bower and Rice (1984) it is possible to obtain the bulk relationship of the soil water retention curve (SWRC) for a stony soil if the relation between the water content and pressure head of the same soil not containing stones is already known.

$$\theta_b = (1 - V_r) \times \theta_{fe} \quad \text{Equation 3}$$

where θ_b [L^3L^{-3}] is the bulk volumetric water content of the stony soil, i.e., the volume of water per total volume of soil including the volume occupied by stones, V_r is the volume fraction of rock fragments and θ_{fe} [L^3L^{-3}] is the water content of the fine earth, i.e., the volume of water per volume of fine soil, excluding the volume occupied by stones. The equation to estimate saturated hydraulic conductivity of a soil containing rock fragments based on K of the same soil not containing stones was derived by Ravina and Magier (1984):

$$K_{s,b} = (1-V_r) \times K_{s,fe} \quad \text{Equation 4}$$

where $K_{s,b}$ denotes the saturated hydraulic conductivity of the stony soil and $K_{s,fe}$ the saturated hydraulic conductivity of the soil without stones. Hydraulic parameters defined in equation 2 (α, n, m and ℓ) for a stony soil are here assumed to be identical to those obtained for its fine earth as explained by Hlavácikova and Novák (2014). Thus, as pointed out by Bower and Rice (1984), the unsaturated hydraulic conductivity function of the stony soil is assumed to have the same shape as the corresponding function of the fine earth but with a lower saturated hydraulic conductivity coefficient $K_{s,b}$, calculated by equation 4.

Novák et al. (2011) proposed a modification of equation 4 introducing a parameter that corrects the non-linear relationship between stoniness and saturated hydraulic conductivity resulting from rock fragments resistance to water flow.

$$K_{s,b} = (1-aV_r) \times K_{s,fe} \qquad \text{Equation 5}$$

where a is a dimensionless parameter that depends on size, shape and rock fragments distribution, and soil texture.

Table 1. Inputs used in every methodological approach employed to obtain the soil water retention curve and soil hydraulic conductivity function from the soil columns.

	Tensiometer (h)	TDR probes (θ)	Soil Water Storage	Evaporation rate
IPM	x	x		
Wind Method	x		x	
Inverse Estimation (h-θ)	x	x		x
Inverse Estimation (h-SWS)	x		x	x

Approach. In order to obtain the desorption branch of the soil water retention curve θ(h) as well as the unsaturated hydraulic conductivity as a function of pressure head K(h) for the soil without rock fragments and the soil with rock fragments, different approaches were used in this study. The inputs used in every approach are summarized in Table 1.

Results obtained from the numerical inversion in HYDRUS were parameter sets according to Equations 1 and 2.

1. Instantaneous profile method (IPM): The instantaneous profile method (Watson, 1966) for calculating K is based on water flux derived from water content change in a compartment as well as influx into and efflux out of that compartment between depths z_i and z_{i+1} over time and hydraulic gradients across the depth interval averaged for the time increment. In this study, the water content change over time was measured with the TDR probes and the hydraulic gradient with tensiometers. These were then directly used to calculate water flux between depth compartments. The hydraulic conductivities were calculated for the time interval based on Darcy's law and then related to the respective pressure head, which was averaged over depth and time for the particular interval and increment, respectively. The fitting of the resulting unsaturated hydraulic data points was accomplished using the RETC code of van Genuchten et al. (1991).

2. Wind's method: Wind's (1969) procedure for determining the SWRC and K as a function of soil water pressure head is a transient method based on an evaporation experiment. An iterative procedure is carried out to estimate the SWRC based on pressure head and total water storage measured over time. No depth-specific measurements of soil water content over time are used as those were not available when the original method was developed. The iterative procedure is briefly described here. For further details see Wendroth et al. (1993), Simunek et al. (1998a), and Wendroth and Wypler (2008). The initial set of polynomial coefficients that are used for describing the θ(h) relationship was arbitrarily chosen. Given the pressure head measurements, water content values were calculated for each time and depth for their respective depth increments and converted to layer-specific water storage (L) by multiplying the computed θ values by their respective compartment thickness. The total soil water storage at a given time is the sum of soil water storage heights in the three different compartments. This calculated water storage was then compared to the soil water storage determined by weighing at the same time. Water contents estimated based on the polynomial coefficients were updated for each time by a correction factor which was the ratio between the measured and calculated total storage, assuming that the estimation error was equally distributed between compartments. Pressure heads were then plotted against the new set of water contents and new polynomial coefficients were obtained through fitting. This process was repeated until the maximum change in water content for all depth and times between two iterations was $<10^{-3}$ cm^3 cm^{-3}. Once the solution converged, the final water content values were adjusted by the correction factor one last time and used for calculating water fluxes between depth compartments as described for the IPM. Accordingly, the fluxes and hydraulic gradients were applied to calculate the hydraulic conductivity for each time interval and depth compartment. The resulting θ-h-K data sets were fitted using the RETC code.

3. Inverse estimation: The inverse solution of Richards' equation is a non-linear parameter optimization method. It minimizes an objective function Φ which describes the difference between simulated and measured values of h and θ obtained at different depths over time during the evaporation experiment, using the Levenberg-Marquardt algorithm (Simunek and van Genuchten, 2012). The inverse mode of the finite-element program HYDRUS-1D was used to estimate the van Genuchten parameters θ_r, θ_s, α, n and K_s from the evaporation experiment data. The objective function was characterized either to pressure head and water content recorded at the three different depths and at different times or to pressure head and total soil water storage at different times. In the first case, inverse solution parameter estimation was accomplished using tensiometer readings and water content measurements from the TDR probes at the different depths. Results of this scenario were denoted as Estimation h-θ. In the second inverse estimation scenario, tensiometer readings and total water storage in the soil core measured by weighing at every time interval were used. Hence, soil water data measured by TDR probes were not used in this second inverse estimation scenario. Results obtained in this second scenario were defined as Estimation h-SWS.

The initial estimates of the soil hydraulic parameters were those associated to the average parameters for a silt loam soil selected from the HYDRUS-1D textural class catalog (Table 2). The upper boundary condition for numerical simulations was the average evaporation rate measured during the evaporation experiment and the bottom boundary condition was set to zero flux.

Table 2. Initial estimate of soil hydraulic parameters used by HYDRUS and RETC programs for every soil column.

	θ_r	θ_s	α (cm^{-1})	n	Ks (cm d^{-1})
Stone-free soil	0.067	0.45	0.02	1.41	10.8
Stony soil	0.067	0.27	0.02	1.41	10.8

The magnitude of the evaporation rates measured experimentally was small, around 0.22 ± 0.05 cm d^{-1} (stony cylinder experiment) and around 0.16 ± 0.05 cm d^{-1} (stone-free cylinder). The fluctuation in the evaporation rates during the experiment was associated with small fluctuations in the temperature and the humidity in the laboratory. As these fluctuations did not change much in magnitude and were cyclic, the average evaporation rate was used as representative of the experimental conditions.

4. Conversion from stone-free soil data to soil with a 40% content of rock fragments: All equations presented so far are based on the assumption that the water retention characteristic and the hydraulic conductivity function of a stony soil are the same as those of its fine earth fraction but being uniformly corrected by the volume of rock fragments present. Based on this assumption, a third set of data was simulated to study if the influence of a rock fragment content of 40% on the soil hydraulic parameters was linearly related to the stone-free SWRC and K(h) functions by a correction factor of 0.4 or whether this relationship was non-linear due to rock fragment resistance to water flow.

Equation 3 was used to convert the SWRC data from the stone-free soil to pairs of θ-h data representing a soil with 40% rock fragments. Hence, V_r of 0.4 cm^3 cm^{-3} represents a soil of 40% rock fragments. New water retention curves were obtained using this approximation. The resulting SWRC were then compared to those obtained from the experiment on the stony cylinder. A similar procedure was conducted for K functions obtained from the different methodologies applied on the results from the stone-free soil. The unsaturated hydraulic conductivity functions resulting for the stone-free soil were fitted according to Equation 2, and then converted for functions in the soil containing rock fragments based on their saturated hydraulic conductivities using equation 4.

Raw data processing.

1. Data treatment: During the evaporation experiment, h and θ were measured every minute and total soil water storage every hour. In order to reduce noise from TDR and tensiometric measurements, the data at a particular time of soil water storage measurement were smoothed by averaging four readings before and after that time.

2. Soil water content adjustment: Total water storage measured through weighing every hour was over or under estimated when calculated from TDR measurements. It is known that the default Topp et al. (1980) equation is not exactly valid for any particular soil, and that a specific soil calibration may become necessary. It was assumed that the error of the TDR-measured soil water content was systematic and not constant but changing over the range of moisture conditions. Therefore, in order to minimize the error, water content values measured by TDR probes were adjusted based on a relationship between soil water content and pressure head. The ratio between total soil water storage calculated from TDR measurements and soil water storage obtained by weighing (S_{mass}) was correlated with the average log (h) of the soil column. In Figure 2a, the relationship between this ratio (S_{TDR}/S_{mass}) and the average log of h observed at the same time during the evaporation experiment is displayed for the stony and stone-free soils.

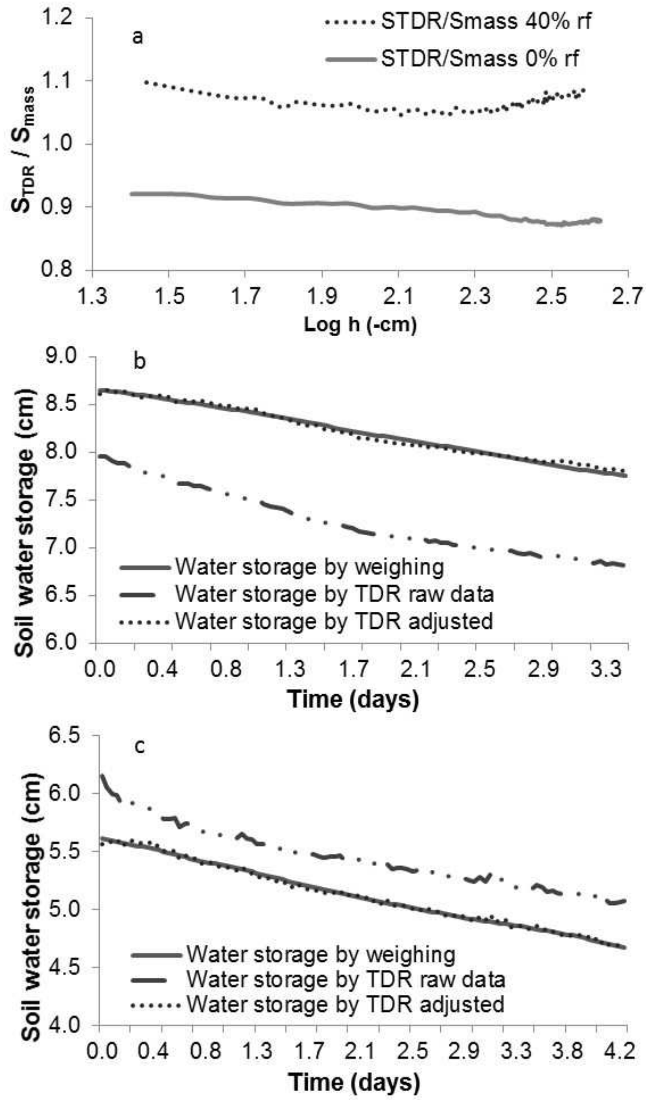

Figure 2. a) The relation between the water storage obtained by TDR measurements and the water storage obtained by weighing (S_{TDR}/S_{mass}) and the log of h for the stone-free and stony soil. Soil water storage obtained by weighing, calculated from raw TDR measurements and calculated from adjusted TDR measurements for: b) stone-free cylinder; c) stony cylinder.

The ratio (S_{TDR}/S_{mass}) differed depending on the soil column analysed. For the column without rock fragments, the ratio decreased as the soil became drier. However, the ratio for the stony cylinder showed the largest difference between water storages at the beginning of the experiment when the soil was wettest.

This difference decreased as the soil became drier but towards the end of the experiment it increased again. Therefore, the ratio between the soil water storage calculated and weighed did not linearly vary with h for the stony soil column. This result led to the conclusion that soil water content measurements using TDR for the two soil columns had to be adjusted independently. For this purpose, the S_{TDR}/S_{mass}-log(h) relationship observations were fitted using a polynomial equation of second order:

$$S_{TDR}/S_{mass}(h)_{i,j} = a\,[\log|h|]^2 + b\log|h| + c \qquad \text{Equation 6}$$

where $S_{TDR}/S_{mass}\,(h)_{i,j}$ was the adjustment factor for every time (i) and depth (j), and a, b and c were the polynomial coefficients. This approach led to a set of correction factors, one for each time interval and depth, used to obtain the adjusted θ values with equation 7:

$$\theta_{ci,j} = \theta_{i,j} \,/\, S_{TDR}/S_{mass}(h)_{i,j} \qquad \text{Equation 7}$$

where $\theta_{i,j}$ is the water content measured by TDR for every time and depth, and $\theta_{ci,j}$ was the adjusted water content.

Table 3. RMSE from the soil water storage values measured and the water storage values obtained from TDR measurements before and after the adjustment.

	RMSE before adjustment	RMSE after adjustment
Stone-free soil	0.945	0.034
Stony soil	0.329	0.022

The effect of the adjustment of TDR measurements on error minimization for the stone-free and the stony cylinders is shown in Figure 2b and 2 c respectively. With the adjustment of water content values, soil water storage based on sample mass and on the other hand based on adjusted TDR measurements became very similar.

3. Pressure transducer tensiometer adjustment: Before the evaporation experiment, the cylinders were left on a Plexiglas plate to reach hydrostatic equilibrium. After several hours of stability of the pressure reading, it was assumed that equilibrium was reached. At that point, the readings obtained from tensiometers installed at the different depths were expected to differ from each other by a height that reflected the 5cm elevation difference between them. Deviations from this number were adjusted as described in Wendroth at al. (1993) and Wendroth and Wypler (2008).

All h and θ results presented in the following sections were processed as described before.

RESULTS AND DISCUSSION

Parametrization of the stone-free cylinder. The results from assessing the validity of the IPM, Wind's method and the HYDRUS inverse estimation for estimating the SWRC in a silt loam stone-free soil column are shown in Figure 3.

For the three soil depths, θ(h) pairs as well as the average θ(h) set are depicted in Figure 3a. At the 3 cm depth, the soil water content was lower at the same h value than at the 8 and 13 cm depths. The θ(h) points resulting from averaging measurements from the three soil depths were closer to points representing the lower depth compartments.

An excellent agreement between the averaged θ(h) data measured with tensiometers and TDR probes during the experiment and the data points determined with the Wind (1969) method was found. Their analytical description is shown in Figure 3b and resulting parameters obtained with RETC (R^2 = 0.979) are listed in Table 4.

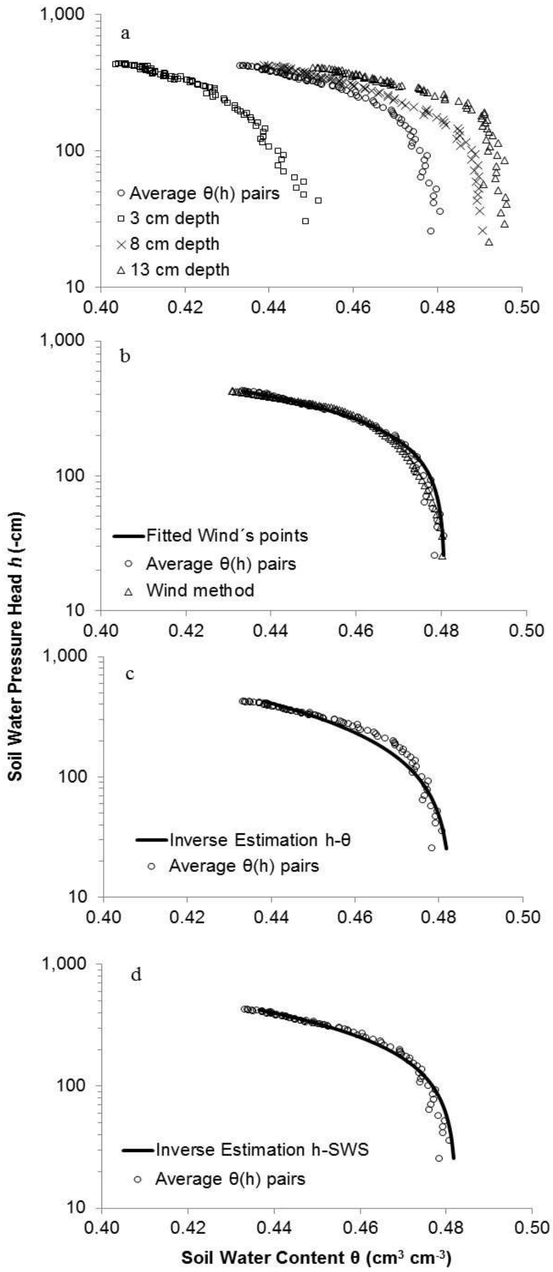

Figure 3. θ(h) relationships obtained in the evaporation experiment and fitted water retention curves determined by the different estimation methodologies for the stone-free cylinder: a) raw data; b) Wind method; c) Inverse Estimation scenario with pressure head and TDR measurements (Estimation h-θ); d) Inverse Estimation scenario with pressure head and total water storage (Estimation h-SWS).

Hydraulic parameters were also estimated using the Inverse Estimation method under two different scenarios, i.e., h-θ and h-SWS, and the results are shown in Figure 3c and 3d, respectively. Soil water pressure heads and soil water contents measured at the three depths were used in the objective function under the Inverse Estimation h-θ scenario. The fitting between measured and predicted values resulted in R^2 equal to 0.989 (Figure 3c).

Table 4. Results of Wind method, inverse estimation and the IPM method for the: a) stone-free cylinder and b) stony cylinder.

	θ_r	θ_s	α (cm^{-1})	n	R^2	Ks (cmd^{-1})	RMSE
Wind method (a)	0.000	0.481	0.001	1.638	0.979	0.528	0.003
Inverse Estimation h-θ (a)	0.000	0.483	0.001	1.319	0.989	1.652	0.041
Inverse Estimation h-SWS (a)	0.000	0.482	0.001	1.579	0.996	0.576	0.030
IPM (a)					0.393	5.913	2.322
Wind method (b)	0.188	0.310	0.003	2.526	0.998	0.477	0.001
Inverse Estimation h-θ (b)	0.000	0.306	0.002	1.698	0.997	0.166	0.034
Inverse Estimation h-SWS (b)	0.092	0.311	0.002	2.103	0.999	0.156	0.008
IPM (b)					0.793	3339.74	3.295

In order to analyse the goodness of these estimated values, correspondence between measured and simulated values was analysed. Simulated water content values deviated from measured mainly for the 3 cm depth and soil water pressure heads best matched the predicted values but deviated once pressure head reached -200 cm. A more flexible approach for optimizing the hydraulic parameters by the Inverse Estimation h-θ was to divide the soil column into three depth compartments: 0-5.5 cm, 5.5-10.5 cm and 10.5-18 cm. As a result, three sets of soil hydraulic properties were obtained, one for each compartment. The agreement between simulated and measured results manifested in R^2 = 0.99, shown in Table 5, was improved compared with the results obtained in the scenario assuming a homogeneous soil column (Table 4). In addition, the root-mean-square-error (RMSE = 0.025) was also improved implying that the goodness of fit between the measured and the estimated data was greater. Thus, water content and pressure head observations were better simulated by the Inverse Estimation h-θ approach allowing for vertical heterogeneity and dividing the soil cylinder into three compartments.

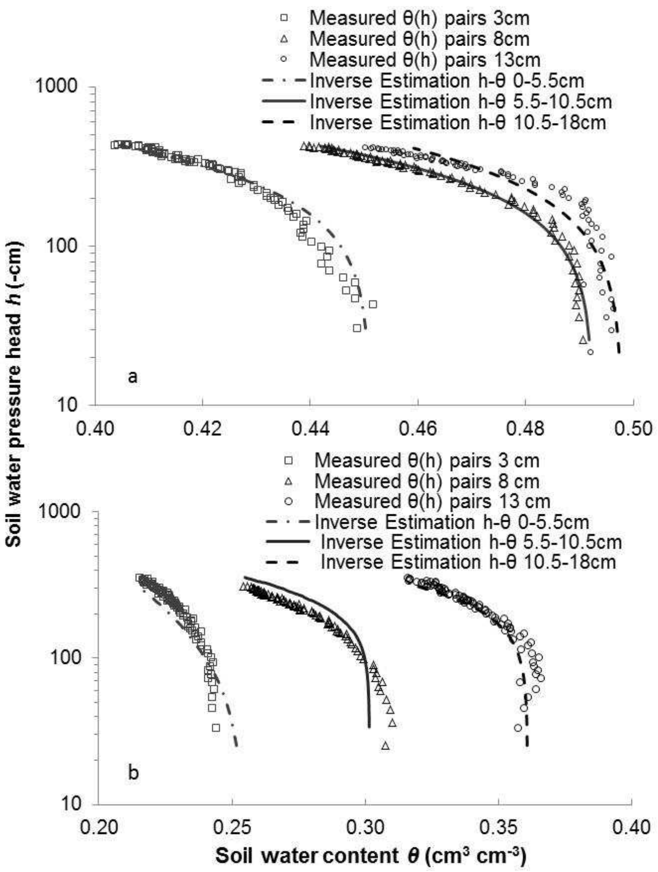

Figure 4. θ(h) data points obtained in the evaporation experiment and water retention curves determined by the Inverse Estimation h-θ methodology using the cylinder divided into 3 compartments, 0-5.5 cm, 5.5-10.5 cm and 10.5-18 cm. a) stony-free cylinder; b) stony cylinder.

Figure 4a depicts the agreement between the soil water retention curve obtained by inverse estimation (Estimation h-θ scenario) and the θ(h) points measured for every soil depth when the soil compartments were analysed independently. The hydraulic parameter values obtained were not very different from the ones obtained using the soil as a whole compartment. Averaging the θ_s values of the three different compartments resulted in 0.48, similar to the value obtained for the homogeneous soil scenario. However, averaging parameter n resulted in a higher value than the one obtained for the unique parameter set scenario in which the cylinder was not divided. Parameter alpha was similar for each scenario studied.

In another inverse estimation scenario tensiometer readings were used as inputs along with the total soil water storage determined by weighing the total mass at each measurement time (Estimation h-SWS). The retention curve obtained by this optimization scenario corresponded well with the averaged θ(h) data points measured experimentally (Figure 3d). The value of R^2 = 0.996, indicated a better fit than for the Inverse Estimation scenario h-θ which characterized the objective function using both h and θ measurements. This result could be explained by the fact that soil water measurements by TDR probes were not included in the h-SWS scenario. In this way, the optimization accuracy reduction associated to soil water content estimation when the cylinder was not divided into three compartments was avoided. The similitude between the soil water storage measured values and the simulated ones using the Inverse Estimation h-SWS method was good. Tensiometer readings and simulated values did not show severe discrepancies.

The agreement between all the retention curves derived from the different estimation methods and the average θ(h) points measured during the evaporation experiment was good despite the fact that for the three depth compartments, different hydraulic parameter values were obtained. The numerical inversion resulted in lower predicted n values and slightly higher values of θ_s than those obtained by the Wind method.

Differences between various estimates of the parameter n could be caused by the fact that the range of measurements in our experiment was limited to the wet and medium range. Therefore, measured data did not support the estimation of this parameter with the accuracy that would have been achieved if our measurements had covered the range between water saturation and drier soil conditions more completely (Simunek et al. 1998a).

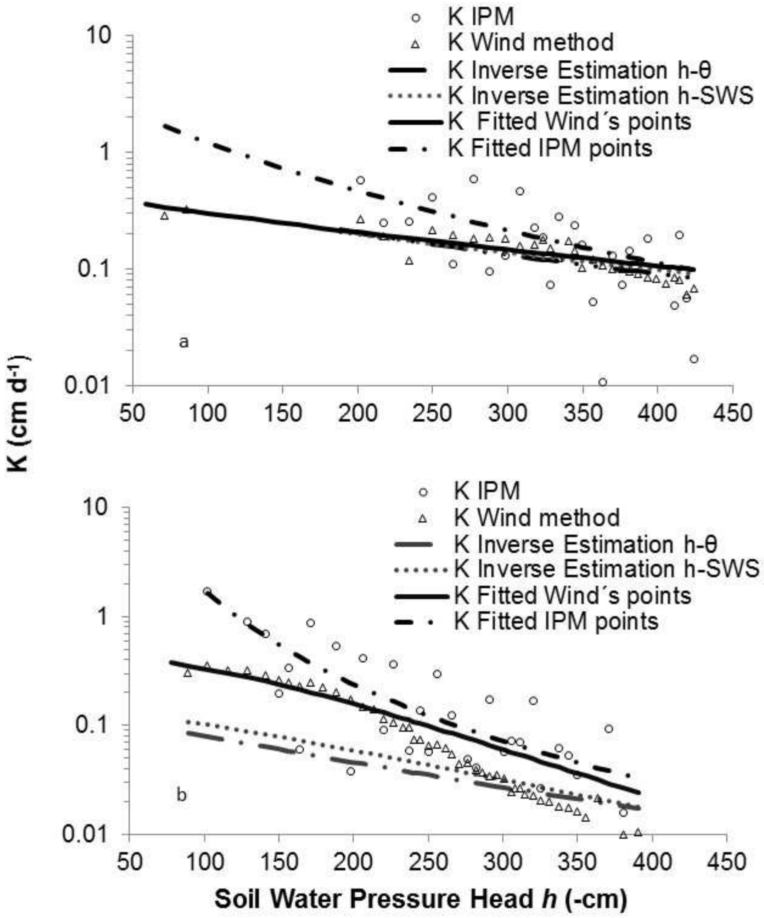

Figure 5. Hydraulic conductivity obtained through the different estimation methods for the a) stone-free cylinder; b) stony cylinder.

The unsaturated hydraulic conductivities determined by the different methodological approaches, considering the soil as a uniform column, are shown in Figure 5a. For the Wind method, no results for K could be obtained in the wet range as long as the threshold value of 0.3 cm cm^{-1} for the hydraulic gradient was not passed. Therefore, K(h) only represented for the range of h<-50 cm. Unsaturated hydraulic conductivity functions obtained via parameter optimization with both inverse estimation scenarios (h-θ and h-SWS) were similar to the K(h) function obtained by the analytical description of the Wind method using RETC. TDR noise caused scatter in the K values computed with the IPM. However, there was less scatter in the K(h) data points obtained by Wind´s method. Thus, differences between the unsaturated hydraulic conductivity functions obtained by the IPM analytical description using RETC to the other methodological approaches could be explained by the scatter of K values.

Parametrization of the stony soil. Results for demonstrating the applicability of the different estimation approaches to obtain hydraulic parameters in the stony soil are presented in this section. Depth-specific and average θ(h) pairs obtained during the evaporation experiment for the stony soil are presented in Figure 6a. Averaging the measurement results of the three depths resulted in a similar water retention relationship as the one observed at the central position (8 cm depth).

The Wind method was applied to the tensiometer and total water storage reading obtained over time for the stony soil. This iterative estimation gave a good water retention curve fit to a 4^{th} degree polynomial equation with a R^2 value of 0.998. A promising result was also obtained after fitting data points obtained with the Wind method to van Genuchten's model by RETC. The shape of the soil water retention curve derived from the fitted Wind results agreed well with the soil water retention points measured (Figure 6b). The stony soil column results obtained from the different estimation approaches are presented in Table 4.

The inverse estimation h-θ scenario was not as good as for the stone-free cylinder. Despite the fact the R^2 value between measured and simulated data was 0.997, the water retention curve shape derived from this inverse parameter estimation did not well represent the θ(h) measured points in the wet range (Figure 6c). Its RMSE value was the lowest for the different inverse estimation scenarios. The assessment of the goodness showed that simulated water content values diverted from the 3 cm and 13 cm depth TDR measurements.

These simulated values were similar to those measured at the 8 cm depth.

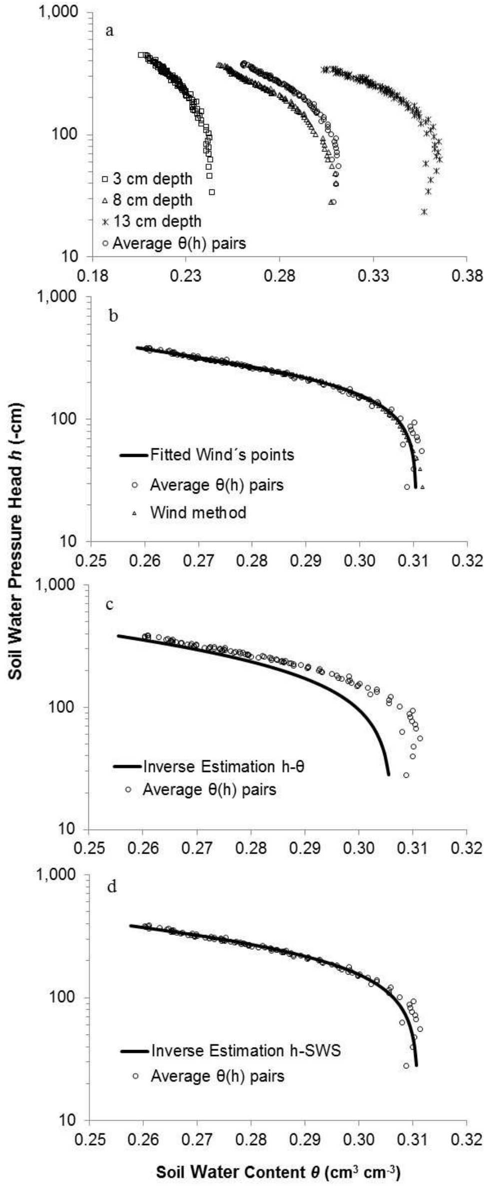

Figure 6. θ(h) relationships obtained in the evaporation experiment and fitted water retention curves determined by the different estimation methodologies for the stony cylinder: a) raw data; b) Wind method; c) Inverse Estimation scenario with pressure head and TDR measurements (Estimation h-θ); d) Inverse Estimation scenario with pressure head and total water storage (Estimation h-SWS).

In the next step, the Inverse Estimation was performed for the three depth compartments 0-5.5 cm, 5.5-10.5 cm and 10.5-18 cm independently, in the same fashion as for the stone-free soil. Results of this scenario are provided in Table 5. Assuming depth-specific soil hydraulic property functions improved the estimation result and the differences between predicted and measured water content were reduced. Figure 4b shows the agreement between the θ(h) points measured for every soil depth and the water retention curves shape obtained by inverse parameter estimation (Estimation h-θ) when soil compartments were analysed separately.

The inverse Estimation h-SWS estimation scenario (Figure 6d) gave the best R^2 result with a value of 0.999 and the lowest RMSE (Table 4). The measured and the simulated water content were in good agreement. In addition, measured and simulated soil water pressure head values were very similar except at the end of the experiment when small discrepancies were noted.

Resulting retention curves from the different estimation methods showed a close match with the average θ(h) points measured during the evaporation experiment except for the Inverse estimation h-θ solution where the curves deviated from each other near water saturation. The θ_s obtained was slightly lower compared to other solution values.

Table 5. Results of parameter estimation using the Inverse Estimation h-θ dividing the cylinder into three different layers, 0-5.5 cm, 5.5-10.5 cm and 10.5-18 cm. a) Stone-free cylinder; b) Stony cylinder.

	θ_r	θ_s	α (cm^{-1})	n	R^2	RMSE
Inverse Estimation θ-h 0-5.5cm (a)	0.028	0.451	0.001	1.606	0.995	0.025
Inverse Estimation θ-h 5.5-10.5cm (a)	0.000	0.493	0.001	1.601	0.995	0.025
Inverse Estimation θ-h 10.5-18cm (a)	0.096	0.498	0.001	1.507	0.995	0.025
Inverse Estimation θ-h 0-5.5cm (b)	0.150	0.255	0.006	1.477	0.999	0.006
Inverse Estimation θ-h 5.5-10.5cm (b)	0.052	0.302	0.002	2.853	0.999	0.006
Inverse Estimation θ-h 10.5-18cm (b)	0.003	0.361	0.002	2.461	0.999	0.006

Differences existed between the estimation methods studied in terms of θ_r and n. As well as for the stone-free soil, the lack of agreement for the n parameter value could be caused by the range of measurements and accentuated by the presence of rock fragments in the soil. As pointed out by Simunek et al. (1998a), θ_r could be estimated with a high level of uncertainty if available measurements belonged to the wet range. In their evaporative simulation experiment the lower value reached by the normalized water content at their range of measurements was far away from the residual content.

Hydraulic conductivity versus pressure head results are presented in Figure 5b. Discrepancies became apparent when comparing the resulting unsaturated conductivity functions obtained from the stony cylinder data considering the soil as a whole compartment. The K(h) values derived from the IPM were scattered similarly to the stone-free soil. This fact could explain the differences with regard to K(h) functions shape derived from the other estimation methods. Figure 5b reveals larger differences between the hydraulic conductivity functions obtained by both inverse parameter estimation scenarios and the Wind method compared with the stone-free cylinder results. Despite the fact that both methodological approaches use similar inputs, the difference between results obtained by the Wind method and by the inverse estimation could be explained by the fact that the latter is a more restrictive approach for optimizing the hydraulic parameters. Thus, a more flexible approach was used to derive K(h) functions from both inverse estimation scenarios (h-θ, h-SWS) by dividing the soil column into three depth compartments (Figure 8). Three resulting sets of soil hydraulic parameters, one for each compartment, were geometrically averaged in order to obtain a unique set. The resulting K(h) functions were compared to those of the stone-free cylinder inverse estimation approach (section above).

Comparison between Water Retention Curves and Unsaturated Hydraulic Conductivity. This section analyses the validity of estimating stony hydraulic properties from those of its fine earth by simply correcting the volume of rock fragments.

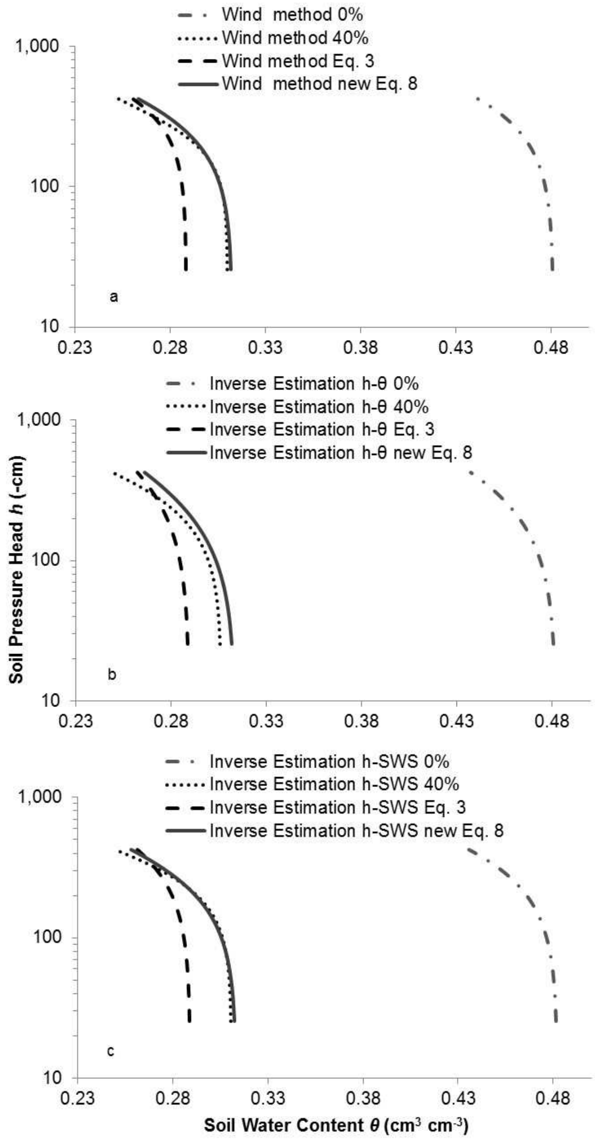

Figure 7. Comparison of the soil water retention curves obtained for the different data sets studied from the stone-free cylinder, stony cylinder and obtained data set using Eq. 3 and Eq. 8 for a) Wind method; b) Inverse Estimation scenario h-θ; c) Inverse Estimation scenario h-SWS.

The difference between the water content of the stone-free and the stony soil columns was not manifested in a constant shift as might be expected from equation 3 but it depended on h. Under the conditions of this experiment it seems that equation 3 (water content of the fine earth cylinder corrected by the volume of rock fragments) underestimated around 5 to 7% the bulk water content of the stony soil column mainly in the wetter range for all scenarios compared (Figure 7). In addition, this overestimation depended on the range of h and seemed to be weaker at more negative values. One hypothesis for explaining this result could be the presence of rock fragments changing the porosity distribution by creating voids and pores of big size that equation 3 was not accounting for (Fies et al., 2002, Gargiulo et al., 2016). Different authors findings supported this hypothesis. Dann et al. (2009) estimated water retention curves from an alluvial gravel soil showing that curves derived from equations seem to underestimate the water content close to saturation, and thus the porosity. Baetens et al. (2009) reported a faster decrease of water content in a stony soil with negative matric potentials than in a soil without rock fragments attributing this result to the increase of pores larger than 0.25 cm. Also, Ma and Shao (2008) and Beckers et al. (2016) found out that soils that have rock fragments resulted in a different fine pore structure than soils without.

Considering these results, the relationship between the water content of the stony soil and the water content of its fine earth fraction seems non-linear and dependent on h. In addition, the water content at saturation for a silt-loam soil with 40% of rock fragments it is not exactly the water content at saturation of its fine earth corrected by the volume of rock fragments but higher. Therefore, deriving the water content of a stony soil by using equation 3 would be too basic. Ravina and Magier (1984) already acknowledged that correcting the soil water content of a soil by simply using the rock fragment volume it contains could imply an over-simplification to represent the effect that these rock fragments exert, at least for determined types of soils like aggregated clays at the lower suction range of the water retention curve. Besides, Hlaváciková and Novák (2014) applied equation 3 to determine bulk water content of a stony soil from the water content of its fine earth. They stated that this equation could be only used under the assumptions that rock fragments do not hold water, macropores are not present in the stony soil, and van Genuchten water retention parameters are identical to those of the fine fraction. In addition, Ma et al. (2010) pointed out that the air-entry value and the water retention curve shape coefficients of some repacked stony soils were not similar to those of the stone-free soil. One solution could be to complement equation 3 as proposed by equation 8:

$$\theta_b(h)= \theta_{r,fe} + [\theta_{s,fe}\,(1\text{-b}V_r) - \theta_{r,fe}] \,/\, \{1 + [\alpha(1\text{+}1 - \text{b}V_r)|h|]^n\}^m \qquad \text{Equation 8}$$

where $\theta_{r,fe}$ (L^3L^{-3}) is the residual water of the fine earth, $\theta_{r,fe}$ (L^3L^{-3}) is the saturated water of the fine earth and b is a dimensionless parameter dependent on size, shape, rock fragment distribution and soil texture. Under the conditions of this evaporative experiment using rock fragments with negligible water retention capacity, mean diameter between 2-6 cm and sub angularly shaped distributed randomly in a silt loam soil, parameter b is equal to 0.875.

The new equation proposed includes the fitting parameters of van Genuchten's model obtained for the water retention curve of fine earth but being $\theta_{s,fe}$ and α adjusted by the parameter b. This adjustment reduced to a minimum the differences between the SWRCs of the stony soil column and the SWRCs derived from the stone-free column using equation 3 (Figure 7). Thus, equation 8 considers the effects of the porosity change created by the rock fragments along the h range of measurements that equation 3 does not account for. Figure 7 shows how the SWRC derived from the new equation 8 was more similar to the SWRC obtained from the stony soil column (40% stones) with the Wind and Hydrus estimation methods. There were some discrepancies at lower pressure head values, explained by some uncertainties in the adjustment of parameter n in the intermediate and wetter range of measurements. There was also a lower agreement between the SWRC of the stony soil (40%) and the SWRC obtained using equation 8 in the Inverse Estimation h-θ scenario due to the less accurate results obtained by this approach when using a homogeneous soil compartment.

Figure 8 shows the comparison between the hydraulic conductivities of the different data sets studied. The K(h) curves of the stony soil belonging to both inverse estimation scenarios (h-θ, h-SWS) were obtained dividing the cylinder into three depth compartments. For all the other cases shown in Figure 8, K(h) curves were derived considering the soil as a whole compartment.

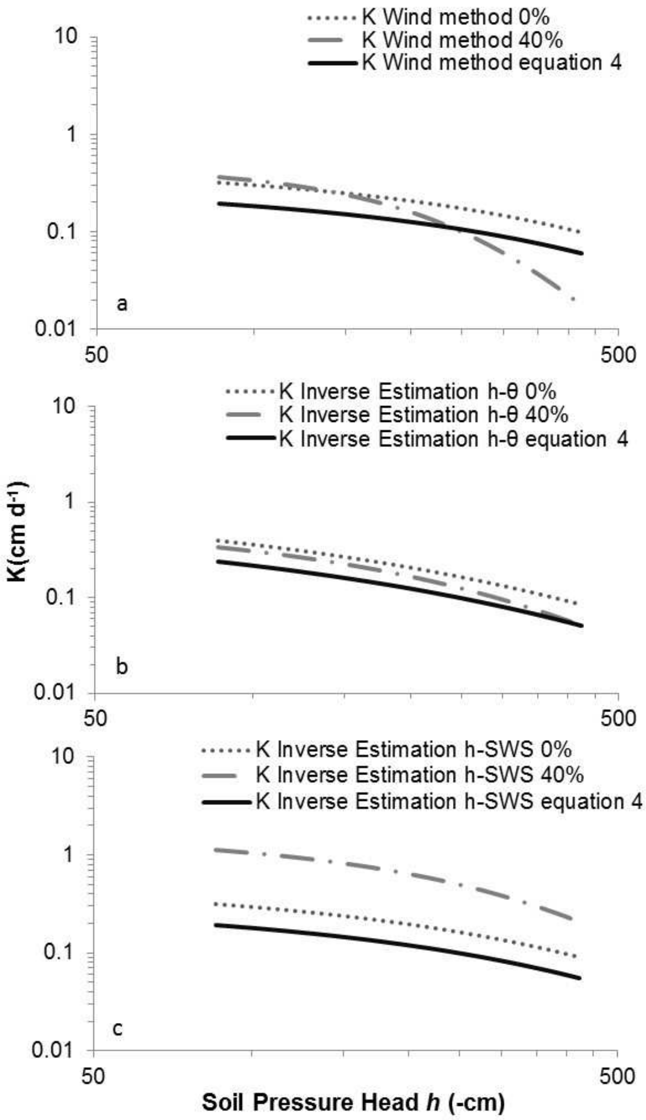

Figure 8. Comparison of the hydraulic conductivity for the a) Wind method; b) Inverse Estimation h-θ approach; c) Inverse Estimation h-SWS approach.

Regardless of the methodological differences (see section above), two common features of the K(h) curve of the stony cylinder can be observed in this figure. First, the values of K derived from the stone (40% stones) and stone-free (0% stones) cylinders measurements in the higher range of pressure head values (h) were systematically higher than those derived from equation 4 for the three different approaches. Second, the shape of the K(h) curves obtained for the stony cylinder denoted a faster decrease of K values with decreasing soil water pressure head than both K(h) curves from the non-stony cylinder and the curve determined using equation 4.

These results support the hypothesis of rock fragments presence creating large pores that change the soil porosity distribution that equation 3 and also equation 4 are not able to account for. Large pores drain faster than smaller ones at lower h. However, when water flow is reduced, their connectivity change decreasing K more rapidly.

Similarly, Dann et al. (2009) measured K(h) in-situ by an infiltration experiment and found that K(h) values close to saturation were higher than those obtained using equation 4. They stated that models used to estimate K(h) generated differences because they did not take into account structural features like macropores. Also, Verbist et al. (2009) reported that rock fragments could have influenced the flux and the saturated conductivity of the soil by creating lacunar pores. In this infiltration experiment they observed that these pores were concentrated in the wetter range and, because of their size, were not able to transport water at low water pressure heads. This is also in agreement with Sauer and Logdson (2002) who observed, during an infiltration experiment, that saturated hydraulic conductivities on stony soils were higher compared to stone-free ones. However, that was not the case for the unsaturated hydraulic conductivity when h values became more negative. Both experiments had in common a resulting steeper decrease of K as h decreased.

Therefore, the presence of larger pores able to conduct water mainly at higher h values (less negative) could be an explanation for the steeper decrease of K(h) in the stony soils column under all estimation scenarios compared in the present study. Furthermore, the effect of rock fragments on the wetting behaviour and resulting K(h) could be a function of whether it is upward capillarity-driven flow process or gravity-driven infiltration process.

The percentage of volume occupied by rock fragments could be also a factor determining the effect that the presence of rock fragments exerts on a soil. Milczarek et al. (2006) tested how hydraulic conductivity was affected by different stone contents. The findings revealed that contents higher than 30% of stones in soils could show higher saturated hydraulic conductivities than soils without. However, the steeper decrease of the hydraulic conductivity function was not so clear. Novák et al. (2011) run an inverse estimation simulation for different sizes and contents of stones while using rounded rock fragments. They identified that saturated hydraulic conductivity decreased with the rock fragment content depending on its size and soil type. However, Ma et al. (2010) found stony soil hydraulic conductivities higher or similar to the stone-free soil depending on the volume occupied by the rock fragments. On the other hand, Wesemael et al. (1995) found that rock fragments contents higher than 30% of volume contributed positively to the macroporosity. More similar to the conditions of the present study, Yang et al. (2013) reported that in their experiment a 40% rock fragment volume in a soil was the fraction at which the water movement in the soil was more benefited by the created macropores than restricted by tortuosity. These agreed with results obtained for the stony soil column at the wet range.

Therefore, applying equation 4 for estimating the stony soil unsaturated hydraulic conductivity from the fine earth seems to be not appropriate for a silt loam soil with a 40% volume of rock fragments with sizes from 2 - 6 cm. This is due to the effect of rock fragments on a soil not depending only on their volume, size, shape, origin or disposition as mentioned in previous studies but also on the pressure head in which water flow is taking place.

The correction factor applied to the stoniness in Equation 5 suggested by Novák et al. (2011) could help to estimate the saturated hydraulic conductivity of a stony soil from its fine fraction by incorporating a parameter that takes into account the rock fragment characteristics. However, the effect of rock fragments on the K(h) shape should be also addressed in order to infer the behaviour of K through the whole pressure head range.

Results from the present study could be applicable to field samples because even though the effect of macropores in repacked soils could be smaller than the effects in the field, the presence of rock fragments in these soil columns could also result in the creation of macropores if the structure of the cylinder is allowed to stabilize (Dann et al., 2009).

CONCLUSIONS

Nowadays, in a scenario of water scarcity and food increasing demand, the optimization of water use in agriculture is a major challenge. Stony soils are spread worldwide and conducting in-situ experiments on them is complicated or near impossible. In these cases, inferring the parameters of water retention from the fine earth properties is the answer and should be accomplished as accurately as possible.

Under the experimental conditions used in this work, both the Wind method and the Inverse Estimation technique were successfully applied to estimate the soil hydraulic properties from the evaporation experiment on a silt loam soil even with a rock fragment volume of 40%. The range of suction in which the experiment was conducted, restricted to medium wet, limited the accuracy of parameter n estimation. Water retention curves derived from the inverse estimation scenario θ-h were improved when a more flexible approach, dividing the soil cylinder into layers, was used.

Results from this work enables to understand that using a simple correction of the fine earth properties by the volume the by rock fragments occupy to estimate the SWRC of a stony soil it is a too simplified approach that does not represent reality. The effect that a 40% volume of 2-6 cm rock fragments exerted on a silt loam soil was not a linear function and varied along the range of pressure head measurements.

A volume of 40% of rock fragments resulted in a positive influence for the unsaturated hydraulic conductivity in the wet range but this value decreased faster with decreasing pressure head, confirming the nonlinear effect of rock fragments on the behaviour of K. Therefore, when the unsaturated hydraulic conductivity of a stony soil is derived from applying a correction to the fine earth values based only on the volume of rock fragments, the accuracy of the estimation will be low and will vary depending on the value of the pressure head.

Based on this research, a new equation to calculate the water content of a stony soil was proposed (equation 8) in which the key element for calculations was not only the volume of stones but the effect that the presence of lacunar pore and the pressure head has on water retention. Further research should be conducted to validate parameter b values for different types of soils, rock fragment volume, size, shape and origin in order to infer its validity. In addition, more studies should be conducted along the same lines that Novák et al. (2011) started by inferring Ks values for stony soils with different textures and rock fragments properties but taking into account the different behaviour of K values depending on h as we have observed in this study.

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Chapter VI

Discusión general

Conclusiones / Conclusions

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CHAPTER VI

Discusión general y conclusiones

Contenidos

DISCUSIÓN GENERAL	**180**
Consideraciones metodológicas en el estudio de la pedregosidad y su influencia en las propiedades del suelo.	180
Efecto de la Agricultura Conservación en la fertilidad, la materia orgánica, las propiedades físicas y la producción de un suelo pedregoso convertido a regadío recientemente.	188
Visión global y consideraciones finales	192
CONCLUSIONES / CONCLUSIONS	**194**
Referencias	199

DISCUSIÓN GENERAL

Consideraciones metodológicas en el estudio de la pedregosidad y su influencia en las propiedades del suelo.

La presencia de fragmentos de roca en el suelo modifica diferentes propiedades del mismo como la disponibilidad y la dinámica del flujo de agua, o propiedades químicas tales como los contenidos de carbono o nitrógeno (van Wesemael et al., 1996; Cousin et al., 2003; Stendahl et al., 2009). Por lo tanto, se ha observado que una adecuada caracterización de dichos fragmentos de roca es indispensable para poder determinar su verdadera influencia.

A pesar de la gran extensión de terreno ocupada por suelos pedregosos, se ha comprobado que no existe un criterio unificado a la hora de clasificar estos elementos gruesos, ya que depende del sistema de clasificación de suelo utilizado (capítulo II). Por ejemplo, FAO (2006) clasifica los fragmentos de roca comprendidos entre 60 y 200 mm como *piedras* mientras que para el sistema de clasificación USDA *piedras* son aquellos fragmentos entre 250 y 600 mm de diámetro (Schoeneberg et al., 2002). Estas discrepancias ponen de manifiesto la importancia de utilizar el término general “fragmento de roca” indicando, además, el tamaño de los mismos, o usar una clasificación específica indicando siempre la referencia utilizada. Esta información se debe completar, siempre que sea posible, con su forma y origen.

Otro aspecto relevante cuando se aborda el estudio de un suelo pedregoso es realizar una correcta cuantificación de la fracción gruesa, pero en este caso atendiendo tanto a su contenido como a su distribución. A pesar de no existir una metodología concreta para el estudio de este tipo de suelos, sí que existe cierto consenso acerca de la necesidad de muestrear el volumen necesario que incluya una porción representativa (Bear, 1972). Este volumen no está definido. Para Butcher et al. (1994) tiene que ser 100 veces la masa del elemento grueso más pesado, mientras que para Novák et al. (2011) o Novák y Knava (2012) la muestra debe contener por lo menos 20 elementos gruesos y ser mayor que 100 cm^3. Por lo tanto, existen ciertas técnicas utilizadas comúnmente en el estudio de suelos como el muestreo mediante barrenas Edelman o cilindros de Kopecky, que no resultan apropiadas en el estudio de suelos pedregosos debido a que limitan el tamaño y número de fragmentos de roca que pueden ser muestreados (Throop et al., 2012). Esto fue confirmado en el estudio llevado a cabo en un suelo clasificado como *Petrocalcic Calcixerept* (Soil Survey Staff, 2014) situado en Olite (NE España) con una textura franco arcillo-arenosa y abundante presencia de gravas (FAO, 2006). El muestreo de suelo mediante una barrena Edelman subestimó un 50-60% el contenido de fragmentos gruesos con respecto al muestreo realizado mediante la excavación de un volumen de suelo considerable para todas las profundidades muestreadas, 0-5 cm, 5-15 cm y 15-30 cm (capítulo II).

La cantidad de elementos gruesos en el suelo suele ser variable, siendo posible encontrar una elevada heterogeneidad tanto en su distribución lateral en superficie como en su reparto a lo largo del perfil. Además, en suelos cultivados, la fracción fina del suelo es susceptible de ser erosionada o migrar hacia capas inferiores debido al laboreo (Poesen y Lavee, 1994), lo que altera la distribución natural de tierra fina y elementos gruesos en el perfil, tal y como algunos autores han señalado (Poesen y Lavee, 1994; Wijdenes et al., 1997). Sin embargo, el análisis de la pedregosidad en la parcela de Olite (capítulo II) no mostró diferencias significativas entre el no laboreo (NT) o el laboreo convencional de la zona (CT) en dos años de estudio. Es por ello que la mayor concentración de elementos gruesos en el horizonte más superficial de este suelo (0-5 cm) en ambos tratamientos pudo ser el resultado del laboreo intenso que se había realizado en esta parcela durante los años anteriores. Por lo tanto, se considera necesario en los estudios tanto de evaluación de suelos pedregosos como en el estudio de los efectos que diferentes manejos puedan tener sobre ellos, que se analice la distribución espacial de la fracción gruesa, así como el efecto de los diferentes manejos en dicha fracción. El uso de herramientas geoestadísticas resulta útil para evaluar la idoneidad y la representatividad de las áreas de estudio. El uso de semivariogramas de la pedregosidad del suelo de Olite (capítulo II) permitió descartar una anisotropía en la distribución espacial de los fragmentos de roca que hubiese podido inducir una tendencia direccional enmascarando los resultados de la evaluación de diferentes manejos en la parcela. Además, gracias a este estudio, se pudo observar que la variabilidad entre los puntos de muestreo era alrededor del 10%, lo que se puede considerar aceptable en este tipo de suelos (Auerswald y Schimmack, 2000). Otra ventaja que ofrece el uso de técnicas geoestadísticas es la posibilidad de determinar la estrategia de muestreo. En el caso de la parcela de Olite los resultados revelaron que un muestreo representativo de los elementos gruesos se podría haber realizado en puntos separados 45-55 m, lo cual hubiese podido reducir el coste en futuras evaluaciones (Cichota et al., 2006).

En cualquier caso, el análisis de los fragmentos de roca es muy costoso en cuanto a tiempo y trabajo (Andrades et al., 2007; Stendahl et al., 2009; Rytter, 2012) lo que fomenta la búsqueda de métodos alternativos a través medidas indirectas como es el caso de la estimación visual. La cuantificación de la presencia de fragmentos de roca a través del análisis de imagen de un catálogo de fotos realizadas a diferentes suelos de Navarra se evaluó en el capítulo II. Esta técnica resultó mejor adaptada para suelos con menor proporción de fragmentos de roca ya que los resultados obtenidos a partir de suelos con un contenido menor del 20% presentaron, en general, una variabilidad menor del 10% con respecto al contenido real. Resultados similares fueron obtenidos por Andrades et al. (2007) señalando que la estimación en este tipo de suelos es compleja debido a la variabilidad de elementos gruesos en los perfiles de suelo en cuanto a su contenido, tamaño o tipología. Además, se pudo comprobar que hay ciertos factores que pueden influenciar la calidad de la estimación y que hay que evitar en el momento de adquisición de las imágenes, como es la presencia de sombras, acentuadas en aquellos suelos con elevados contenidos de fragmentos de roca donde unos pueden sombrear a los otros o la adquisición de fotos en suelos en los que el laboreo ha dejado tormos de gran tamaño que pueden ser confundidos con elementos gruesos. La toma de imágenes debe realizarse con atención también en aquellos suelos cuyo matriz fina es del mismo color que los fragmentos de roca o en los que se detecte la presencia, aunque sea en pequeña proporción, de residuos de cultivos, hierbas adventicias, cultivo o incluso plásticos de uso agrícola.

Una vez los fragmentos de roca son correctamente caracterizados, es importante analizar su efecto en las funciones del suelo. Es conocido que su presencia disminuye el espacio ocupado por la fracción fina limitando, por lo tanto, las propiedades intrínsecas de ésta (Poesen y Lavee, 1994). Esto se pudo verificar en los capítulos III y IV en los cuales los contenidos de N, P, K y materia orgánica de la tierra fina fueron referidos al total del suelo tras ser corregidos por el contenido gravimétrico de elementos gruesos presentes. Debido a la elevada concentración de fragmentos de roca en los primeros centímetros del suelo, la reducción fue más drástica en esa profundidad mientras que en el resto de profundidades (5-15 cm y 15-30 cm) la reducción fue un 10-15% menor. Por lo tanto, una distribución no homogénea de los fragmentos de roca a lo largo del perfil del suelo puede variar el comportamiento en profundidad de las propiedades del suelo cuando éstas no son referidas a la fracción fina. Es por ello que indicadores tales como el contenido de carbono orgánico particulado (C-POM), la estratificación en profundidad de la materia orgánica y el nitrógeno (N) o la interacción entre el carbono orgánico del suelo y el N, utilizados para el estudio de la calidad de diferentes suelos de manera satisfactoria (Franzluebbers, 2002; Virto et al., 2007; Imaz et al., 2010; Aziz et al., 2013) pueden no ser válidos para un suelo pedregoso. En el capítulo IV se estudió el efecto del contenido heterogéneo de fragmentos de roca a lo largo del perfil del suelo en la parcela de Olite. La distribución vertical del carbono orgánico del suelo (SOC), el C-POM y el N se vio afectada tras la corrección realizada por el contenido de elementos gruesos presentes en cada profundidad. Sin embargo, el ratio de estratificación del C-POM se mantuvo como un indicador robusto en el suelo pedregoso estudiado. Esto confirmó su aptitud como indicador de cambios en el manejo del suelo, lo cual ya había sido expresado anteriormente por varios autores para otros tipos de suelos (Six et al., 2002; Imaz et al., 2010; Ladoni et al., 2015). De la misma manera, los ratios C:N y C-POM:SOC se mantuvieron estables al ser el cociente entre dos variables. Esto los convierte en una buena elección para suelos con una pedregosidad heterogénea a lo largo del perfil del suelo. En cualquier caso, aunque algunos autores inciden en la validez de expresar los contenidos de nutrientes o materia orgánica en la tierra fina ya que es la fracción que atribuye las propiedades al suelo (Throop et al., 2012), estos resultados ratifican la necesidad de referir dichos indicadores a la totalidad del suelo (incluyendo los elementos gruesos) con el objetivo de realizar evaluaciones más precisas, especialmente al referir las propiedades del suelo a unidades de superficie.

En este sentido, las metodologías utilizadas para trasladar las propiedades de la tierra fina al volumen total del suelo deben ser consideradas cuidadosamente para garantizar su idoneidad (Stendahl et al., 2009; Rytter, 2012; Throop et al., 2012). Este es el caso de la cuantificación de stocks en suelos pedregosos. La conversión del contenido de carbono o nitrógeno en el suelo a unidades de superficie es una fuente de variabilidad para la comparación de diferentes estudios que además puede inducir a error (Rytter, 2012; Throop et al., 2012) tal y como se observó en los resultados obtenidos en el capítulo IV. Considerando solamente la fracción fina contenida en todo el volumen del suelo, incluyendo el volumen de fragmentos de roca tal y como describen Throop et al. (2012), el stock de SOC alcanzó valores de 47,9 ± 1.1 Mg C ha^{-1} para la profundidad de 0-30 cm. Sin embargo, cuando en los cálculos se tuvo en cuenta el contenido de SOC de la tierra fina, pero se utilizó la masa total del suelo y el volumen total del mismo corregido por el volumen de fragmentos de roca presentes, el stock de SOC alcanzó valores de 57,2 1.1 Mg C ha^{-1}. En este suelo con un contenido medio de elementos gruesos del 40%, el uso de la masa y el volumen total del suelo (éste último corregido por su pedregosidad) sobreestimó alrededor del 20% el stock de SOC en comparación con la metodología recomendada por Throop et al. (2012) para suelos pedregosos. Este resultado demostró que es necesario utilizar una metodología apropiada para este tipo de suelos cuando se realizan cálculos de stocks con el objetivo de evitar errores que serán más importantes cuanto mayor es la pedregosidad del suelo. Para ello es necesario corregir la densidad aparente del suelo por la pedregosidad, pero también la concentración de nutrientes del mismo. En la misma línea, Schrumpf et al. (2011) comprobaron que a mayor contenido de elementos gruesos mayor era la variabilidad del contenido total de carbono y Rytter (2012) afirmó que un error a la hora de tener en cuenta el volumen real que los elementos gruesos representa en el suelo pude conducir a sobreestimaciones de los stocks. Por lo tanto, estos resultados evidenciaron que cuando se trabaja con suelos pedregosos es de vital importancia especificar no sólo los métodos de muestreo y contenido final de fragmentos de roca sino las metodologías aplicadas para calcular los stocks.

De la misma manera, es importante tener en cuenta la metodología utilizada para obtener las propiedades hidráulicas de un suelo pedregoso ya que el efecto que los fragmentos de roca generan en el suelo es complejo. Por un lado, su presencia disminuye el volumen de la tierra fina y por tanto la capacidad de retención de agua del suelo. Así mismo, reducen el área a través de la cual ésta puede circular disminuyendo la conductividad hidráulica. Sin embargo, pueden generar el efecto contrario ya que su presencia facilita la creación de poros lacunares en la interacción entre la tierra fina y los fragmentos de roca, así como cambios en la distribución de la porosidad total (Bouwer y Rice, 1984; Sauer y Logsdon, 2002; Ma et al., 2010; Novák et al., 2011). Hoy en día existe mucha incertidumbre debido a que este efecto depende del tipo de suelo y del valor de pedregosidad, tamaño, forma y origen de los elementos gruesos (Cousin et al., 2003; Gargiulo et al., 2016). A esto se le suma la dificultad de realizar muestreos *in situ* en este tipo de suelos, lo que dificulta su estudio o directamente conlleva su estimación de manera indirecta. Por lo tanto, como obtener muestras inalteradas en este tipo de suelos es complicado (Ma et al., 2010; Novák et al., 2011; Hlaváciková y Novák, 2014), en el capítulo V se comprobó la validez de la utilización de columnas de suelo alteradas para comprender el impacto de la pedregosidad en las propiedades hidráulicas. Además, se evaluó la idoneidad de la metodología comúnmente utilizada que deriva las propiedades hidráulicas de un suelo pedregoso simplemente corrigiendo las propiedades de su tierra fina por el volumen de fragmentos de roca. Para ello se utilizó el método de evaporación desarrollado por Wind (1969), así como la estimación inversa mediante HYDRUS-1D. Estos métodos resultaron eficaces para estimar los parámetros hidráulicos de dos columnas de suelo de 18 cm de longitud construidas una con un suelo franco limoso y la otra con ese mismo suelo, pero incluyendo un volumen de elementos gruesos del 40%. La bondad de la estimación usando HYDRUS fue un poco menor debido a que las mediciones llevadas a cabo en el experimento no alcanzaron el rango de succiones más altas, lo que hizo que la estimación de ciertos parámetros fuera menos precisa (Šimůnek et al., 1998). Además, en el caso de la columna de suelo con fragmentos de roca, se alcanzaron mejores resultados usando un enfoque más flexible que permitía dividir dicha columna en compartimentos y realizar las estimaciones para cada uno de ellos. Al derivar las propiedades hidráulicas del suelo pedregoso a partir de su tierra fina, simplemente corrigiendo el volumen de fragmentos de roca presentes, se comprobó que este método no consiguió reflejar la realidad del suelo estudiado bajo las condiciones experimentales de este estudio. Es más, esta aproximación metodológica subestimó alrededor del 5 al 7% las mediciones del contenido de agua realizadas en la columna de suelo con fragmentos de roca en los rangos de succión más bajos. A mayor succión este valor fue disminuyendo. Este resultado fue debido a que en un suelo franco limoso el efecto que ejerció la presencia de un 40% de elementos gruesos con un tamaño comprendido entre los 20 y 60 mm en su capacidad de retención de agua y su conductividad hidráulica no fue lineal, sino que dependió también del rango de succión. Este efecto se atribuyó a cambios en la porosidad del suelo pedregoso debidos a huecos o poros de mayor tamaño creados por la presencia de elementos gruesos. En la misma línea, diferentes autores reportaron la creación de poros de gran tamaño y cambios en la porosidad del suelo debidos a la presencia de fragmentos de roca (Sauer y Logsdon, 2002; Baetens et al., 2009; Dann et al., 2009; Yang et al., 2013; Gargiulo et al., 2016). Por lo tanto, al corregir las propiedades hidráulicas de la tierra fina solamente por la pedregosidad presente, el efecto de estos poros no se tuvo en cuenta. En el caso específico de la capacidad de retención de agua del suelo, parece más conveniente en vista de los resultados obtenidos, realizar una estimación a partir de la tierra fina utilizando otra corrección que sí pueda tener en cuenta el efecto que genera la porosidad creada por la presencia de los fragmentos de roca a lo largo de todo el rango de succión tal y como se propone en el capítulo V. Para la conductividad hidráulica algunos autores establecieron un umbral de pedregosidad a partir del cual el efecto de la porosidad creada por la presencia de estos fragmentos de roca era mayor que la tortuosidad de flujo creada, lo que resulta beneficioso para la conductividad hidráulica del suelo (Milczarek et al., 2006; Ma et al., 2010). Este umbral es bastante variable, pero en las condiciones experimentales de este estudio se comprobó que bajo una pedregosidad del 40% el efecto fue positivo a rangos de succión bajos, pero al aumentar ésta, la conductividad disminuyó rápidamente. Esto hecho ratificó la presencia de poros de gran tamaño capaces de conducir agua principalmente cuando la succión es baja. Por lo tanto, además de tener en cuenta la cantidad, origen, tamaño y forma de los elementos gruesos a la hora de derivar la conductividad hidráulica de un suelo pedregosos a partir de su tierra fina tal y como propone Novák et al. (2011), se debería abordar su diferente comportamiento a lo largo del rango de succión debido a la nueva porosidad creada.

Además de todo lo expuesto hasta ahora, la presencia de fragmentos de roca puede modificar el funcionamiento de un suelo. Esta hipótesis podría explicar el incremento significativo de materia orgánica en la parcela recientemente transformada a regadío descrita anteriormente en un breve periodo de tiempo, 2 años (capítulos III y IV). Cuando un suelo pedregoso recibe materia orgánica, a pesar de tener un volumen menor de tierra fina, los inputs que recibe son los mismos y por tanto tienden a concentrarse en esa fracción (Poesen y Lavee, 1994). Esto permitiría detectar cambios debido al manejo más fácilmente como sería el caso de la introducción de cultivos más productivos en el sistema capaces de generar mayor cantidad de biomasa y por tanto mayores inputs.

Efecto de la Agricultura Conservación en la fertilidad, la materia orgánica, las propiedades físicas y la producción de un suelo pedregoso convertido a regadío recientemente.

La transformación a regadío de suelos con limitaciones naturales para la producción como son los pedregosos, permite incrementar sus rendimientos debido a que el agua ya no supone un factor limitante. Bajo las condiciones del ensayo realizado sobre el *Petrocalcic Calcixerept* (Soil Survey Staff, 2014) situado en Olite (NE España), se pudo observar que, en tan sólo dos años, el SOC, así como el N del suelo se incrementó de manera significativa (capítulos III y IV). Este incremento pudo ser consecuencia de los mayores rendimientos de los cultivos debido a la disponibilidad de agua, así como a la introducción de cultivos con potenciales productivos mayores dentro de la rotación. En la misma línea Gillabel et al. (2007) y Denef et al. (2008) indicaron que los incrementos de la biomasa producida tras la transformación a regadío resultan en mayores inputs de C incorporados al suelo. Otros autores señalaron que este incremento de C del suelo también viene asociado a cambios en la dinámica de la mineralización de la materia orgánica favoreciéndose su descomposición (Apesteguia et al., 2015; Zhou et al., 2016). Sin embargo, el caso aquí estudiado, tal y como explica Follet (2001), parece indicar que el mayor contenido de C que entró en el suelo se acumuló a una tasa superior que la de mineralización, escenario que se mantendrá hasta que se alcance una situación de equilibrio entre el C entrante y saliente o hasta que se produzcan cambios en el manejo del suelo. Esto apoya la teoría expresada Trost et al. (2013) que indica que el potencial secuestro de carbono bajo un sistema en regadío es dependiente de las condiciones locales de estudio.

La introducción de la Agricultura de Conservación en un suelo pedregoso transformado a regadío llevó asociado una serie de efectos sobre la fertilidad del suelo, además del ya mencionado en el contenido de materia orgánica y sobre las propiedades físicas del mismo que, junto con el ahorro de combustible (Crosson, 1982), podrían justificar la adopción de esta práctica por parte de los agricultores de zonas semiáridas en regadío con el objetivo de practicar una agricultura más sostenible. En el caso de la fertilidad del suelo, la introducción del no laboreo (NT) tuvo un efecto significativo principalmente en los primeros 5 cm, provocando una mayor estratificación de estas propiedades con la profundidad. Esta mayor acumulación de nutrientes en la capa más superficial del suelo en comparación con el laboreo convencional, observada previamente en otros estudios (Deubel et al., 2011; Papini et al., 2007), pudo ser consecuencia de una mayor acumulación de residuos en la capa superficial del suelo resultante de practicar un no laboreo.

De la misma manera, el efecto del NT sobre la materia orgánica se observó principalmente en los primeros 5 cm del suelo (capítulos III y IV). El contenido de SOC se incrementó con respecto al laboreo convencional tan sólo dos años después de la introducción de esta práctica como respuesta a una mejor protección de la materia orgánica por los agregados del suelo y/o la falta de acceso de los microorganismos a la misma (Christopher et al., 2009; Huang et al., 2015). De hecho, el sector de la parcela de Olite en el que se practicó el no laboreo solamente durante un año mostró un mayor contenido de SOC, que aunque no significativo, se podría esperar que lo fuera después de un año más bajo esta práctica (capítulo III). La observación de diferencias en un periodo de tiempo tan corto, a diferencia con otros estudios en climas semiáridos (Dick et al., 1991; Virto et al., 2007; Álvaro-Fuentes et al., 2014) se pudo deber, como se comentó anteriormente, a la introducción del regadío produciendo mayores inputs de C junto a la capacidad de un suelo pedregoso de concentrar estos inputs en la tierra fina. Esto apoya la teoría de Melero et al. (2002), quienes indicaron que suelos de texturas gruesas responden mejor al NT debido a su menor contenido de materia orgánica y por lo tanto mayor potencial de respuesta frente a la no perturbación de los agentes de unión.

La capacidad de secuestro de C en los 30 cm del suelo fue similar en los dos tipos de laboreo alcanzando el stock de C medido valores de 47,9 ± 1,1 Mg ha^{-1}. Estos valores se sitúan dentro del rango medio reportado para el área Mediterránea y España (Lugato et al., 2014; Rodriguez Martín et al., 2016). La evaluación de la calidad del suelo bajo este sistema se realizó en el capítulo IV y se complementó utilizando otros indicadores como la fracción lábil de la materia orgánica (C-POM), su estratificación, así como el carbono mineralizable. De acuerdo con otros estudios (Six et al., 2002; Imaz et al., 2010; Ladoni et al., 2015), el C-POM fue el parámetro más sensible a los cambios de manejo del suelo mostrando diferencias significativas con el laboreo convencional en un periodo de tiempo menor que el reportado por otros autores (Aziz et al., 2013; Dimassi et al., 2014). Los ratios de estratificación en profundidad mostraron valores bajos, aunque similares a otros estudios de la zona (Melero et al., 2012), siendo mayores en cualquier caso para el no laboreo. Esto ratificó la hipótesis de una mayor acumulación de los residuos en las capas superficiales del suelo bajo este manejo. De la misma manera, las tasas de respiración mostraron valores mayores en los primeros 5 cm del suelo para el NT. En vista de estos resultados, se confirmó la hipótesis de que el suelo estudiado presentaba un potencial de mejora en cuanto a su calidad al incrementar su contenido de materia orgánica en la capa más superficial del suelo bajo prácticas de Agricultura de Conservación. Este hecho pude ayudar a mejorar sus funciones productivas, así como disminuir su susceptibilidad ante posibles degradaciones.

El efecto positivo del NT sobre la disponibilidad de agua del suelo se observó a dos niveles (capítulo III). Por un lado, se incrementó la capacidad de retención de agua del suelo de los primeros 5 cm a niveles de succión bajos. Esto fue atribuido a un cambio en la porosidad con un incremento de poros de mayor tamaño capaces de transportar y almacenar agua a esos niveles de succión. Además, la representación de las curvas de retención de agua ratificó un cambio en la porosidad ya que bajo NT este suelo perdía agua más lentamente al incrementarse la succión. Más del 60% de la porosidad estaba compuesta por poros mayores que 9 µm, sin embargo, en tan sólo dos años, se incrementó el número de poros con un tamaño comprendido entre 6-9 µm. A niveles en los que la retención de agua depende de la adsorción y por lo tanto está más influenciado por la textura de la tierra fina que por la estructura (Loll y Moldrup, 2000), no hubo diferencias asociadas al laboreo. Resultados similares fueron reportados por Bescansa et al. (2006) o Papipi et al. (2007). Por otro lado, el ensayo llevado a cabo sobre la curva de secado del suelo en función del laboreo (capítulo III), demostró cómo el NT disminuyó la evaporación del suelo. A pesar de la elevada presencia de fragmentos de roca en superficie, que podrían haber actuado como el principal factor limitante de la evaporación independientemente del laboreo utilizado (Zhang et al., 2011), la capa de residuos que permanecieron sobre la superficie junto con su interacción con los fragmentos de roca presentes redujo la pérdida de agua bajo NT. Este efecto ya había sido observado previamente en otro tipo de suelos no pedregosos (Fabrizzi et al., 2005; Verhulst et al., 2011; Salem et al., 2015). Además de secarse de una manera más lenta, tras realizar un riego en el que el suelo alcanzó la capacidad de campo, la pérdida de agua fue un 35-40% menor que en el laboreo convencional. Este resultado podría ser la consecuencia de una mejor distribución de los poros y el aumento de la capacidad de retención de agua del suelo corroborando los resultados descritos anteriormente. Por lo tanto, la Agricultura de Conservación se posiciona como un sistema interesante en regadío por su capacidad de facilitar un uso más eficiente del agua.

A pesar de que este tipo de agricultura es conocida por incrementar los rendimientos de los cultivos en climas áridos o semi áridos, su efecto sobre cultivos producidos en áreas más húmedas no suele ser siempre positivo, incluso su práctica disminuye la producción en algunos casos (Lahmar et al., 2010; Pittelkow et al., 2015). Esto resulta como consecuencia de eliminar el agua como factor limitante de la producción, lo que conlleva que la mayor retención de agua bajo NT ya no suponga una ventaja a la hora de alcanzar mayores rendimientos. Bajo las condiciones de regadío del ensayo realizado en Olite (capítulo III), en el que la disponibilidad de agua no es un factor limitante, al igual que en las regiones húmedas, se observó una menor emergencia de los cultivos bajo el laboreo de conservación. La combinación de una menor temperatura del suelo junto a la presencia de fragmentos de roca dificultando la siembra (Pérez de Ciriza et al., 2004; Fabrizzi et al., 2005) redujo notablemente el número de plantas en este laboreo. Sin embargo, debido al potencial de ahijado del trigo y del sorgo para compensar la bajas nascencia, esto efecto no se tradujo en una disminución de la producción. En el caso del maíz, la baja nascencia fue compensada en el segundo año con un mayor índice de cosecha. Por lo tanto, el laboreo de conservación no mejoró los rendimientos en comparación con el laboreo convencional pero tampoco los disminuyó tal y como reportaron Salem et al. (2015). La combinación del no laboreo, con el mantenimiento de residuos sobre la superficie junto con la rotación de cultivos explicaría que no se produjese la disminución de rendimiento observada a corto plazo por algunos autores (Pittelkow et al., 2015).

Visión global y consideraciones finales

El uso de suelos pedregosos para la producción agrícola se está expandiendo como consecuencia de una mayor demanda de recursos edáficos para la agricultura. Los fragmentos de roca que los componen son muy variables en cuanto a cantidad, tamaño, forma u origen, lo que les confiere particularidades muy diversas. Por tanto, su presencia y efectos en diferentes propiedades del suelo tanto físicas como químicas no se pueden obviar. Esta presencia debe ser específicamente documentada de manera que se puedan realizar caracterizaciones y evaluaciones de la manera más precisa posible sobre los efectos que diferentes prácticas y manejos realizados en este tipo de suelos pueden conllevar.

La práctica de la Agricultura de Conservación en suelos bajo climas áridos y semiáridos está bastante extendida debido a sus efectos positivos en estas zonas donde el agua es un factor limitante. Sin embargo, se presenta como una técnica cuya adopción en suelos pedregosos de zonas semiáridas en regadío podría ser justificada debido a otros beneficios como la realización de un uso más eficiente de los recursos. De esta manera, además, se cumpliría con los requerimientos actuales de practicar una agricultura más sostenible.

En el marco de esta tesis doctoral se han llevado a cabo una serie de trabajos e investigaciones que han permitido avanzar en el conocimiento de los suelos pedregosos y las implicaciones de una correcta caracterización de los mismos. Este conocimiento ha esclarecido la importancia e idoneidad de aplicar metodologías adecuadas que puedan ser utilizadas en la evaluación tanto de la fertilidad de este tipo de suelos, la materia orgánica presente y su calidad, así como de las propiedades hidráulicas, todo ello partiendo de las características de su tierra fina. Además, se ha evaluado la interacción de estos suelos con prácticas agrícolas de Agricultura de Conservación como es el no laboreo. Esto ha aportado datos del potencial que presenta este tipo de suelos marginales tras su conversión a regadío para secuestrar carbono orgánico y mejorar la optimización del riego, principalmente en la capa más superficial del suelo, que es también la más sensible a los procesos de degradación.

Los estudios desarrollados a lo largo de la presente tesis han aportado nuevo conocimiento científico y, además de ello, han abierto nuevas cuestiones que podrían ser resueltas a través de posibles líneas de investigación futuras. Por un lado, se ha observado la importancia de realizar una adecuada caracterización de la pedregosidad de un suelo, aunque en la actualidad no existe una metodología específica y generalizable para hacerlo. Por lo tanto, es necesario desarrollar una estandarización de los procedimientos a llevar a cabo durante los muestreos y caracterizaciones de los suelos pedregosos, así como durante el proceso de conversión de los datos a unidades de superficie. De esta manera se podría realizar la comparación entre valores de diferentes estudios, así como garantizar la validez de los resultados. Al mismo tiempo sería interesante avanzar y validar métodos de estimación indirecta de la pedregosidad que permitieran ahorrar recursos y que pudiesen ser implementados a nivel práctico. Por otro lado, sería necesario continuar investigando sobre la validez de la estimación propuesta para la capacidad de retención de agua del suelo a partir de las propiedades de la tierra fina en función de distintos tipos de suelo, contenidos de fragmentos de roca, tamaño y origen de los mismos. De la misma manera, sería necesario profundizar en el comportamiento de la conductividad hidráulica de un suelo pedregoso, no atendiendo solamente a las singularidades de los elementos gruesos sino también a su diferente efecto a lo largo de los valores de succión que permitieran realizar estimaciones más precisas del comportamiento del flujo de agua. En vista de los resultados aportados en esta tesis, también sería interesante mantener la investigación a largo plazo sobre el efecto del no laboreo en la capacidad de secuestro de carbono y su dinámica en este tipo de suelos cuyas condiciones han cambiado debido a la transformación a regadío. Por último, sería interesante destacar el interés de estudiar el comportamiento en suelos pedregosos de otros indicadores de calidad de suelo cuya validez ha sido ya comprobada en suelos sin fragmentos de roca, como es el caso de los biológicos.

CONCLUSIONES / CONCLUSIONS

Las conclusiones obtenidas de los estudios que conforman esta tesis son las siguientes / *Conclusions obtained from the studies that are part of the present thesis are the following*:

1. No existe una metodología estándar para caracterizar y estimar los contenidos de fragmentos de roca de un suelo. Sin embargo, es de vital importancia muestrear un volumen de suelo lo suficientemente representativo ya que técnicas comúnmente utilizadas en el estudio de suelos como el muestreo mediante una barrena tipo Edelman, pueden subestimar el contenido de fragmentos de roca un 50-60%. El uso de herramientas geoestadísticas puede ser un complemento para evaluar la representatividad del muestreo y detectar patrones en las distribuciones espaciales que induzcan subjetividad en el análisis.

A standardized methodology to characterize and estimate the rock fragments content of a soil does not exist. However, it is of vital importance to sample a volume representative enough for avoiding misinterpretations. Techniques commonly used for soil sampling like the use of Edelman type augers may underestimate 50-60% the rock fragment content of a soil. The use of Geostatistical techniques may *be useful for evaluating the adequacy of the sampling scheme and also to detect spatial patterns that could induce bias on the soil analysis.*

2. La estimación visual del contenido de fragmentos de roca de un suelo mediante el análisis de imagen presenta un potencial de aplicación principalmente en aquellos suelos con un contenido menor del 20%. Para optimizar los resultados, a la hora de tomar las imágenes se deben evitar las sombras, la presencia de plásticos, restos de cultivos o plantas emergentes, suelos recientemente labrados con elevada presencia de tormos o suelos cuya matriz es de un color similar al de los fragmentos de roca presentes.

The visual estimation of the rock fragment content of a soil by image analysis shows a potential application for those soils with a content lower than 20%. In order to optimize the results, some aspects should be considered during image acquisition: avoid shadows; the presence of plastics, crop residues or plants; recently ploughed soils with aggregates of big size; soils whose matrix and rock fragments show a similar colour.

3. La práctica del no laboreo en suelos pedregosos de climas semiáridos bajo regadío dificulta la nascencia de las plantas, lo que puede ser solventado mediante el uso de maquinaria especialmente preparada para este tipo de suelos, o usando variedades con elevada capacidad de compensación ante bajas implantaciones del cultivo.

The practice of no-tillage in semi-arid gravelly soils under irrigation difficults plant emergence. This issue can be overcome by using adapted machinery specially prepared for this type of soils, or by sowing varieties with a high capacity to compensate low crop implantations.

4. La adopción de prácticas de no laboreo en suelos pedregosos mediterráneos en conjunto con el regadío ha contribuido a incrementar la acumulación de carbono orgánico del suelo principalmente en la parte más superficial del mismo en un breve periodo de tiempo, 2 años. Esto resulta especialmente interesante en este tipo de suelos con limitaciones para la producción de cultivos o susceptibles de ser degradados.

Adoption of no-tillage techniques in Mediterranean gravelly soils in combination with irrigation has contributed to increase soil carbon accumulation at the soil surface in a short period of time, 2 years, which is especially relevant for this type of soils with limitations for crop production or susceptible of being degraded.

5. La práctica de no laboreo ha sido capaz de incrementar la capacidad de retención de agua de los primeros centímetros de un suelo pedregoso mediante un aumento y un cambio en la distribución de la porosidad, principalmente de los poros comprendidos entre 6-9 µm en tan sólo dos años. Además, la presencia de residuos en superficie ha disminuido la evaporación del mismo. La combinación de los dos efectos puede contribuir a realizar un manejo más eficiente del riego.

The practice of no-tillage has improved the water holding capacity of the upper layer of a gravelly soil in only two years by increasing and changing its porosity, mainly through pores between 6-9 µm. In addition, the presence of residues at the soil surface has decrease its evaporation. The combination of both effects can contribute to manage irrigation in a more efficient way.

6. La metodología utilizada para la conversión de nutrientes a unidades de superficie en suelos que contienen fragmentos de roca

debe ser especialmente considerada para evitar errores en las estimaciones, por ejemplo, de su potencial capacidad de almacenamiento de carbono, agua y nutrientes. La elección de una metodología de cálculo incorrecta en un suelo con un volumen de fragmentos de roca próximo al 40%, puede llegar a sobreestimar su contenido de carbono en un 20%. Este error está directamente asociado a la pedregosidad que presente el suelo y se agrava conforme se incrementa su valor.

The transformation of nutrients to a spatial basis in soils containing rock fragments should be especially considered in order to avoid estimation errors, e.g., their potential carbon storage capacity. The selection of unappropriated calculation methodologies in a soil with a volume of rock fragments close to 40%, may overestimate its carbon content by 20%. This error is directly associated with the soil stoniness and is aggravated as its value increases.

7. La materia orgánica particulada se ha mantenido como un indicador robusto sensible a cambios de manejo en un periodo muy corto de tiempo adecuado incluso para suelos pedregosos en regadío. El uso de indicadores de la funcionalidad de suelos pedregosos tales como la estratificación en profundidad, pueden verse afectados por la presencia de una distribución heterogénea de los fragmentos de roca a lo largo del perfil y deben ser siempre referidos al volumen total del suelo y no sólo a la tierra fina.

Particulate organic matter stood out as a robust soil quality indicator sensitive to soil management changes in a very short period of time, also adequate for gravelly soils under irrigation. Indicators for soil functioning in soils that contain rock fragments, e.g. stratification ratio, can be affected by the presence of a heterogeneous distribution of these rock fragments through the soil profile. They should always be referred to the total soil volume and not just the fine earth.

8. El uso tanto del método de Wind como la técnica de Estimación Inversa pudieron ser aplicadas con éxito a una columna de suelo franco limoso de 18 cm de longitud para estimar sus propiedades hidráulicas a partir de un experimento de evaporación incluso cuando el 40% del volumen se ocupó con fragmentos de roca. El rango de succión utilizado limitó la estimación del parámetro n. Un escenario más flexible que permite dividir la columna del suelo en capas permite mejorar la estimación de las propiedades hidráulicas a partir de la estimación inversa con datos de sondas TDR y tensiómetros.

The use of both the Wind method and the Inverse Estimate technique were successfully applied to a silt loam soil column of 18 cm of length to estimate the soil hydraulic properties from an evaporation experiment even with a rock fragment volume of 40%. The range of suction used in the experimental conditions limited the accuracy of parameter n estimation. A more flexible scenario, dividing the soil column into layers, improved the results from the inverse estimation scenario that used TDR and tensiometer data.

9. La estimación de las propiedades hidráulicas de un suelo pedregoso a partir de las propiedades de su tierra fina usando como corrección el volumen de fragmentos de roca presentes, es una simplificación que no representa el efecto real que ejerce la presencia de estos elementos en el suelo. La interacción entre los fragmentos de roca y la tierra fina de un suelo franco limosos con una pedregosidad del 40% genera cambios en la porosidad cuyo efecto tanto en la curva de retención del agua del suelo como en su conductividad hidráulica no es lineal sino dependiente del valor de la succión ejercida.

Estimating the hydraulic properties of a stony soil from the properties of its fine earth only by correcting them with the volume the rock fragments occupy is a simplification that does not represent the real *effect the presence of rock fragments exert. In a silt loam soil with a 40% of stoniness, the interaction between the rock fragments present and the fine earth, modifies the porosity affecting both the water retention curve and the hydraulic conductivity not linearly but dependent on the suction exerted.*

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